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Module size investigation on fast chargers for BEV

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Technical report 2018:3
Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
SE-412 96 Gothenburg
Sweden, 2019

Cover page: Super chargers in Ulricehamn

Abstract

Fast chargers as defined by CharIN are DC-chargers up to a power level of 50 kW and are usually built to charge one vehicle. New High Speed Chargers can have a power up to 150 kW and Ultra High Speed Chargers up to 350 kW. They are to be used by some of the biggest battery vehicles and the charger could be made out of smaller modules that charge the big battery vehicles as well as several smaller vehicles at the same time.

The report investigates how module size to a 150 kW charger influences the charge process of a vehicle type that will be available fairly soon. The best is to use many small modules if the efficiency can be high enough. A module size of 17-30 kW is a rather good alternative and nine/five such modules could provide 150 kW. The fixed cost of low power electronics has with this size become low compared to the power circuits. The size is so low that it is possible to combine several modules to the needed power. If a lower number of bigger modules are to be used the knowledge of the target vehicle is important, otherwise for instance four modules can behave worse than three modules. Just one big module is not recommended as it is inflexible in terms of charging different sized vehicles and the utilisation of the charger is low. If the charger are divided in two modules the charger will be much more flexible and with the ability to charge two vehicles at the same time a better utilisation of the charger is achieved. With more modules it's easier to adapt the power to different sized cars and in the studied examples the charging time can be decreased with up to 5 %. For the second arriving car the charge time can be 10 % lower with five modules compared to three.

A medium voltage module based on MMC and DAB is suggested for further investigations. The module could be connected to 10-40 kV grid and could be an alternative instead of a 50 Hz transformer.

Another route is to further work on a structure with a big grid-converter and a common DC-link for support of batteries or renewable energy.

Preface

This report concerns fast chargers and how they are built. It is a prestudy, economically supported by the Swedish Electromobility Centre.

There are many aspects to electromobility and the bare fact that cars will drive around almost noise and emission less is fantastic. The batteries, power electronics and electric machinery can be topic for research in a wide-spread way. The components can be optimised and scrutinised in many ways, for instance electromagnetic disturbances, life-length, life cycle investigations and influence on the electric grid are interesting topics.

Thanks to Henrik Holmer at ABB who have showed and informed me about ABB's new fast chargers. Mats Josefsson have been helpful with how the cars work in charging situations. Thanks also to Emma Grunditz and Torbjörn Thiringer for as always good discussions and reviewing the text. Also thanks to Viktor Alatalo who helped me out when stuck on Python and obejct-oriented programming.

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1. Introduction to fast chargers

1.1 Background

A movement towards electrification of the transport sector is ongoing as a response to climate change and pollutions in the cities. Electric buses show promising results and some of the car producers such as Tesla are mass producing electric vehicles and Volkswagen have started to takes order on their first mass produced electric car. Many car producers try to make both plug-in hybrids and battery electric cars, BEV, that totally rely on big batteries. Batteries are continuously performing better and have lower cost. The cars that are introduced now have better range and performance compared to the first generation. Even heavy vehicles are on the agenda and the most extreme vehicle is Tesla Semi with a battery of approximately 1 MWh.

There are three ways of electrifying the vehicles, first and obvious is to use big batteries and performance similar to ordinary vehicles. It will need a development of the batteries and that cost of the batteries will be lower and there are also issues with supply of raw-material. Another way is to supply the electricity continuously from the roads, so called electric road systems (ERS). The third alternative is producing hydrogen from electricity via electrolysis of water. The future electric supply will rely on more renewable power such as wind and solar power. The energy flow is non predictive and the grid has to be stabilised with storage system for the energy that cannot be consumed immediately. Batteries can store energy and why not use the batteries in the vehicles. If there also are fuel cell vehicles hydrogen could be produced and stored for later consumption.

While a system with small batteries (plug-in vehicle or a car relying on ERS) will have to charge or find an ERS already after the first 30-60 minutes of driving, a system with bigger batteries can on the other hand more or less rely on charging at hours with low load from other electricity users. Depending on the driving distance, a bigger battery will for some result in no need for charging at work. The batteries may be charged when there is a surplus of for instance wind energy in the system. In this system, fast chargers will be an extra opportunity for those that have long driving distances that surpass what can be charged during the night or if the trips are longer than the vehicle range.

If the electricity is stored directly in batteries, a much better efficiency is achieved compared to using hydrogen and fuel cells. Another possibility with the batteries is to deliver energy back to the grid and if there are many vehicles available for this we can avoid peak power generation from fossil fuelled plants. Taljegard , [1], has shown that cars with vehicle to grid,(V2G), ability can be useful in the grid. With smart control of the charge process, energy from the batteries in the cars may smooth out the irregularities from renewable energy.

Vehicle to Grid, V2G, can be utilised by cars standing still and are connected to the grid. The on board charger, (OBC), can have double direction ability for delivering power to the grid. Normally this power is somewhere between 3.6 to 11 kW, and in the future this power could be used. The possible potential for delivering power to the grid is 14 GW if 4 million cars are standing still and able to deliver energy to the grid with the power of 3.6 kW. As a comparison the Swedish Power

Reserve is 1.3 GW for distribution areas 3 and 4, which is the southern and most populated half of Sweden.

The batteries in cars can have a profound effect on the electric grid in the future. Parked cars can be used as an enormous battery that helps and stabilises the electric grid. Fast chargers on the other hand works in the opposite direction, when a BEV needs energy from a fast charger, most certainly the driver wants action as fast as possible so that he or her can continue the trip. I.e. the power should be delivered at once, and if a large number of chargers have to do the same, there will be high power on a single part of the electric grid. In this sense the fast charger works as an electric road system, which more or less delivers electric power to all the vehicles that travels on a certain part of the road. Due to that reason it has been investigated to install energy storage in conjunction with the fast charger.

Fast charger of a battery electric vehicle, i.e. charger of Type IV having power higher than 50 kW, are used at long trips or heavy users, such as taxi and delivery cars. When driving longer than the nominal range of the battery the fast charger can relatively fast replenish the battery. The European standard CCS as well as the Japanese standard Chademo-chargers that have been used until now are rated at 50 kW. Some 100 kW chargers are in operation in Sweden and an initiative for building Ultra chargers (>150 kW) for long distance travels is ongoing in Europe.

In [12] it is stochastically simulated how the power demand on a fast charging station is distributed during a week. The station has 9 charging spots and it is dimensioned to serve 1000 EV's. If it is acceptable with a waiting time for less then 10 minutes for 99.7 % of the drivers it is enough with 5 charging spots and a maximum power of 250 kW. While if all 9 charging spots are used, the waiting time is close to zero and a maximum load on the station is 400 kW. Included in the charging station there is a lead battery storage and PV-cells. If the study is extrapolated to Sweden an all electric fleet of Swedish cars (4.8 million cars) would require 24000 charging points and a peak power of 1.2 GW. However the study is made in the Flemish Region of Netherlands and Sweden could need more long trips compared to that region. A similar study without the electric storage is reported on in,[13], where they find an interesting result stating that ten 50 kW chargers are needed for 1000 BEV's but if the charging power increase to 150 kW the need is only 1.8 charger, i.e. the number of chargers are only one fifth of the 50 kW chargers. The 150 kW chargers are also more frequently used in their study.

A modern fast charger comprises a converter connected to the grid, with capability to exchange a sinusoidal current from the grid. A DC-link provides a short term energy storage which feed power to a converter that feeds a transformer and finally the transformer secondary voltage is rectified. The transformer provides necessary galvanic insulation between the grid and the vehicle.

In Figure 1, a schematics is shown that presents the different parts of a converter.

Early versions of the fast charger had an 50 Hz transformer instead of the high frequency option shown in Figure 1.

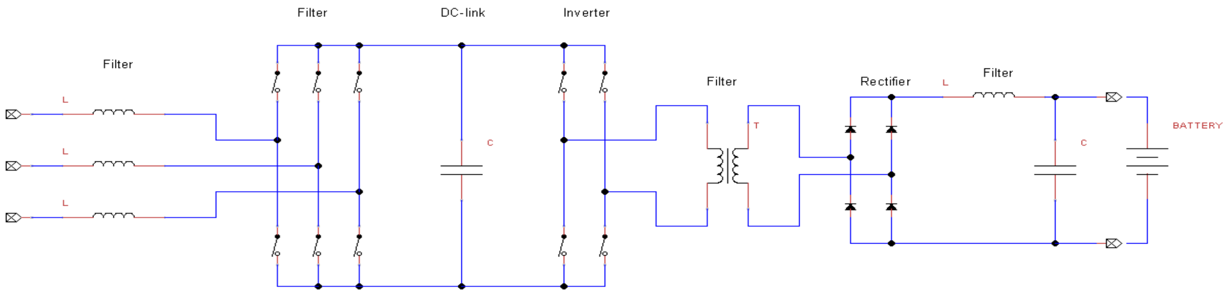

Figure 1. Fast charger, 400 V's input to the left and output to the battery on the right side.

A modern charger from ABB or Delta comprises a set of modules with relatively low power rating. The typical fast charger Terra, see Figure 2, charger have five 10 kW modules that can be connected either to the CCS or the Chademo port.

Figure 2. Terra from ABB, 50 kW, with one CCS, one Chademo and one three-phase connector.

A massive implementation of EV's that rely on fast chargers for long distance trips will need a lot of fast chargers. How many there will be is a matter for discussion but anyway it is of interest to find ways to make them economical and efficient. The chargers are expensive and so is the construction work on-site. Therfore, considering the high number of chargers that have to become operational within some years, it's interesting to find a solution that is flexible, both in operation and on commissioning. Installing many chargers at each site will lower the installation cost but each unit has to be simplified and more economical. This report focus on the fast chargers, if they can be built in a modular fashion and if there are benefits when connecting the electronics directly to the medium voltage grid.

1.1 CCS-charger

The standard solution in Europe is the Combo connector, which is used in the 50 kW-chargers. CharIN, a consortium for drafting requirements and accelerating the use of EV's defines two classes of High Power, HPC 150 and HPC 350. A voltage up to 1000 V can be used in the chargers with highest rating. The charge current is 375 A at peak rating which is solved with a cooling fluid inside the cable. Porsche are deploying cars with nominal voltage of 800 V and the ability to charge at 350 kW. And Audi already sell e-tron with the ability to charge at 150 kW up to 80 % of the SOC.

Figure 3. Combo connector, cable part and car inlet.

1.2 Super charger

The super charger is a fast charger for Tesla cars and it has been free of charge for those who owns a Model S or X. With the new Model 3 a cost for charging is introduced. Tesla Motors are some years in front of the development and they are already building large scale sites for charging. One example is the Kettleman City-site in California, which has a 40 charge-point installation. The biggest in Scandinavium is the one in Rygge, Norway with 34 charge-points. Figure 4 shows the site in Ulricehamn, with 10 charge points and 5 cabinets for the modules.

Figure 4. Ulricehamn, cabinets for power electronics and the charge points.

The supercharger has a power rating of 130 kW and two charge-points are sharing the power rating. A cabinet power two charge-points and in the cabinet 12 modules of 11 kW can be connected to the charge-point that have the highest power demand, see Figure 5.

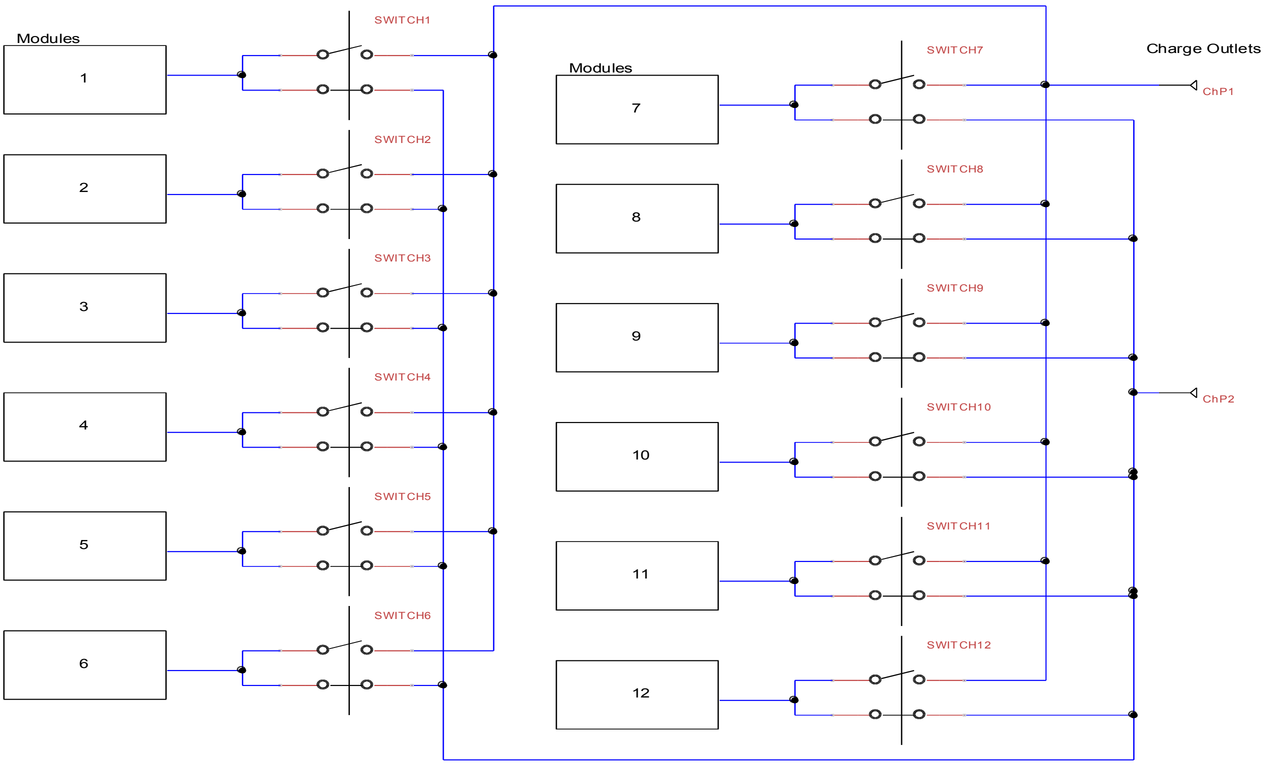

Figure 5. One cabinet with 12 modules of 11 kW each.

The module of 11 kW is the same unit as delivered with the cars as on-board charger, which means that Teslamotors have a high volume production of the units. Using the same unit in the chargers has been helpful in lowering cost.

Tesla are now establishing super charger V3 that have maximum power of 250 kW and a car is always guaranteed maximum power.

1.3 New generation of CCS-charger

The high power charger, with up to 150 kW power rating is produced by several companies. ABB, Delta, see Figure 6, and Chargepoint are some of them. All of them have an ambition to be able to charge several cars with different power.

Figure 6. Vision from Delta and 175 kW charger in Kristinehamn.

Delta has several high power chargers operated by Dalakraft in Rättvik, Leksand and Säter. ABB and Fortum have built Sweden's first 175 kW-site in Kristinehamn. The latter one will have six charge-points and two are operational in July 2018.

An initiative called Ultra-e are building a net of Ultra fast chargers (HPC 350) along main routes in Germany, [6]. The first one are operational since Dec. -17, with a power rating of 175 kW which will be upgraded to 350 kW. A similar initiative Ionity are also building ultra-fast chargers, [20,21].

An important factor is the installation cost which has earlier been up to 25 000 Euro / charger. ABB claims that the new chargers will have an installation cost around 5 000 Euro / charge-point. Plus cable.

1.4 Charging behaviour used in this report

Model 3, Leaf with bigger battery, VW ID3 and a new version of Hyundai Ioniq have battery size roghly between 45-75 kWh and higher charging power than the first generation of cars. I think that we will see a lot more of the behaviour in Figure 7, where an assumed charging behaviour is depicted. It is based on users data for the Model 3, see Appendix A where some different charge curves have been registered by Fastned who runs a net of fast chargers in Netherlands. Similar behaviour as Figure 7 is used for other batteries, i.e. the battery can be charged with full power up to 50 %.

The battery can be charged with 100 kW up to SOC=50 %, which is at 1100 s, and then the battery limits the charge power and there is a drop of power towards 42 kW at SOC=80 %, which is reached at 2050 s. This means that a charger will have a surplus of power capacity for half of the charge time. The surplus power could be fed to another vehicle.

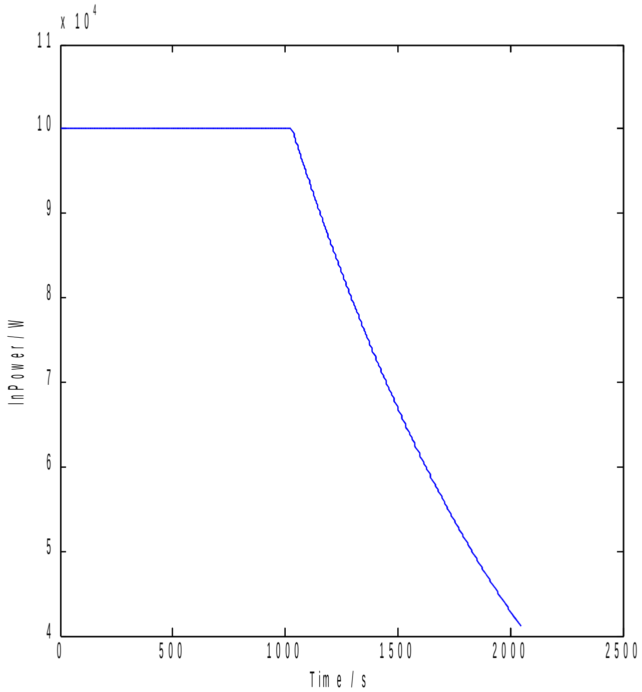

Figure 7. Assumed charge process to studied battery.

A simple battery model is used according to Figure 8 and it is tuned to simulate the charge process of the battery in Figure 7. A voltage source representing the internal voltage in series with a resistor is used for representing the battery and similar models are used for other battery sizes.

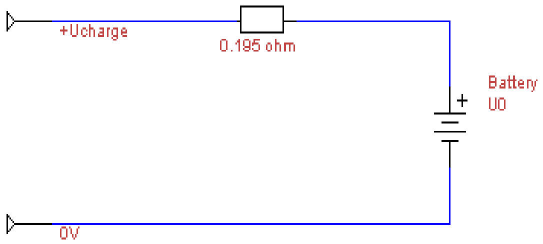

Figure 8. Simple battery model used in this report

The internal voltage, U_0, is assumed to be linear with State Of Charge, SOC,

$$U_0 = 300 + 100 * SOC$$
$$SOC \in (0,..,1)$$

And the charging voltage, Ucharge, is limited to 400 V, which means that at 100% SOC the possible charge current is zero. The resistance is quite high and represents a power loss of 12 kW at maximum current, which isn't representative for the battery. The conclusion is that the power limitations observed for the Tesla Model 3 cannot be due to the battery resistance.

High power charging of Li-ion batteries impose heat, stress and ageing to the batteries. Formation of dendrites at cold weather is another challenge. Next generation of batteries will probably have solid electrolytes, (Toyota VW BMW...), [19],which have new challenges in ion conductivity, which could limit the charging power. Nevertheless the work on increasing the charging power is ongoing.

1.5 Limitations of this study

This report will not handle displays and payment solutions that is some important aspects of the chargers. The report concentrates on the actual circuits that controls and converts electric power from the grid to the car.

2. Main components of a module

In this part we study the fundamental power circuits of a charger and later on the cost and efficiency is calculated. The findings are used for simulations of the charging process with different number of cars and finally some possible developments of the power electronics are discussed.

2.1 High frequency design, connected to 400 Vac

The design in Figure 1, can be more detailed to Figure 9, where it is assumed that the transformer is fed by a resonant link, a so called LLC-converter. The resonant link isn't necessary but makes it possible to switch the components at zero current, (ZCS). Zero current switching is beneficial for lowering the power losses of the power electronics. In order to minimise the need for complicated cooling circuits low power losses are necessary. For instance the secondary diodes could be exchanged to a controlled rectifier with MOSFETS and in that way lower the voltage drop in the components.

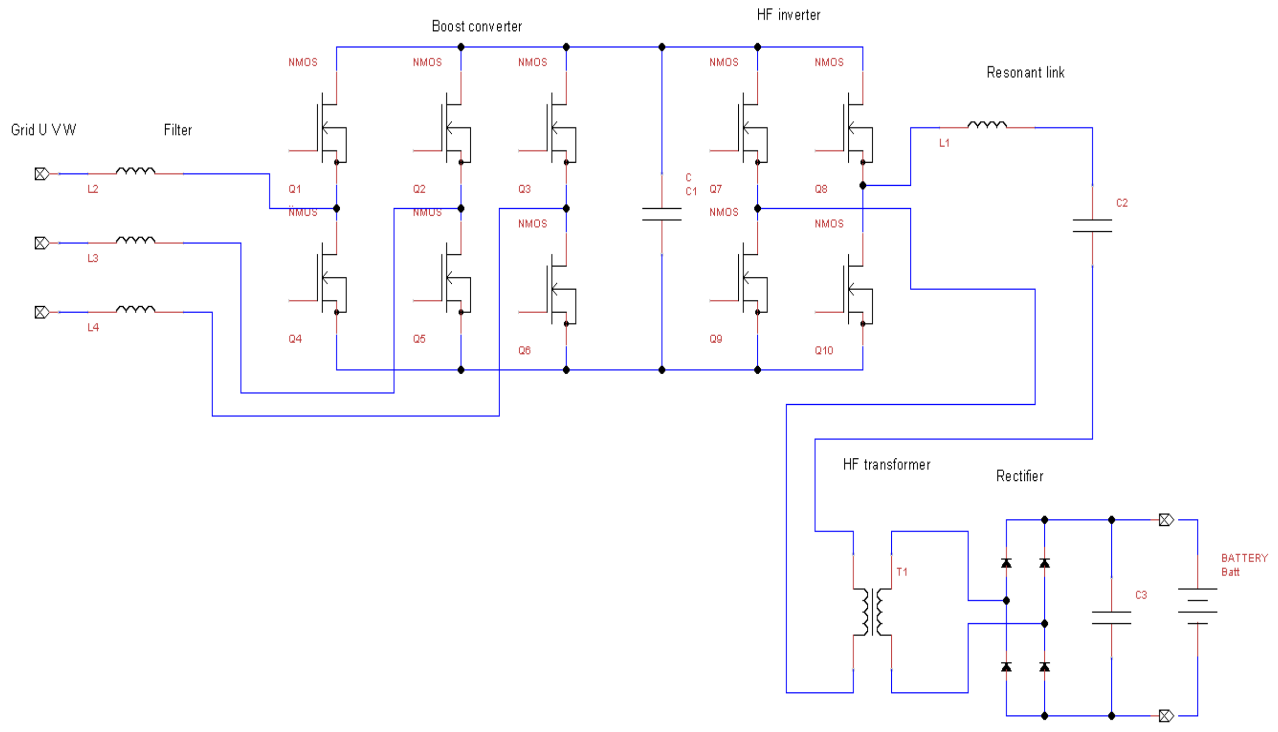

Figure 9. Converter topology.

The grid is connected to a six-pulse boost converter via a filter. The filter is probably made with at least one inductor and a capacitor per phase, which isn't shown in the figure. The boost converter have six silicon carbide MOSFET's, Q1-Q6, that control the voltage of the DC-link.

Q7-Q10 produce a square wave voltage to the high frequency transformer and the resonant LC-link.

Two versions can be outlined, the first version is a module that has the complete functionality of Figure 9. It includes the rectifier part and the high frequency DC-DC-converter. The other version has a big converter on the grid side and a central DC-link. The grid-side converter can preferably be done with a three-level converter. A so called Vienna converter needs smaller inductances than a 6-pulse converter.

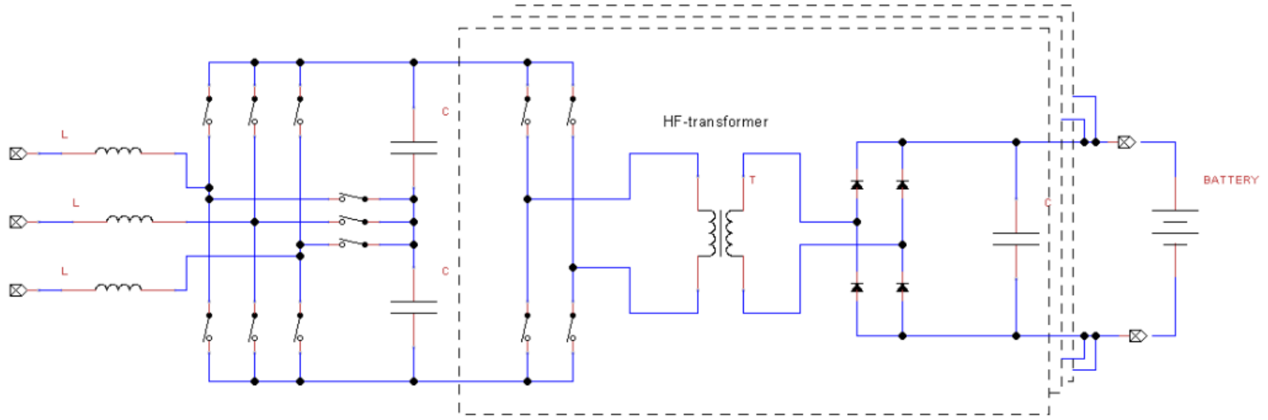

Figure 10. Three-level grid converter.

If the chargers shall be supported with batteries or renewable energy it can easily be fed into the big central DC-link.

2.2 Power electronics

The power electronic components rectifiy the grid voltage and feed the transformer on the primary side and on the secondary side the voltage is rectified again to the battery.

SiC-components are a technique that is quite new and are competing with IGBT's which have been the main choice for high voltage (1200 V) applications. MOS-fets made of SiC have higher voltage rating and lower switching losses compared to the Si-counterparts. The material Silicon Carbide can also withstand higher temperature which could be used to emitt more power losses from the component. The heat is driven by the temperature difference between the chip and the cooling surfaces, so a high temperature means handling of more power losses to the cooling circuit compared to more low temperature components. This is however a future thing because the temperature of the components are limited of other reasons inside the components.

Some examples of interesting work on SiC pinpoints the ability to build highly efficient and small power electronic devices. Zhang et.al.,[5], have evaluated a converter to the Prius PHEV and the use of SiC improves the efficiency of the converter with 20 %, the equivalent fuel consumption decrease from 2.98 L/100 km to 2.44 L/100km and makes it possible to simplify the thermal management.

2.3 DC-link

On the DC-link there is a capacitor that stores energy from the rectifier and delivers energy to the HF-inverter. The amount of energy is quite low even if the power is high. The stored energy is delivered to the next step in a couple of ms.

The capacitor may be made of electrolyte-capacitors which have high capacitance but have the draw-back of limited life-length. Another option is a special DC-link polypropylene capacitors which have better life-length and current handling capability.

A common DC-link have been proposed by Rivera et.al., [2,3]. The idea is to have a big and central conversion from the grid and create a DC-link with approximately 1000 V, that can handle high power and from the DC-link several modules charge several vehicles. Each module in this case consists of a simpler DC-converter, see Figure 10.

If renewable energy, solar or wind is combined with a charger it's beneficial if the energy is fed into a common point where it can be shared between all the modules. In that way the energy is easily guided to the charger that needs power. This idea has also been investigated by, Tan et.al. [16], the focus is on the inductor to the inverter but there is an idea of charging several vehicles from the same DC-link, see Figure 11.

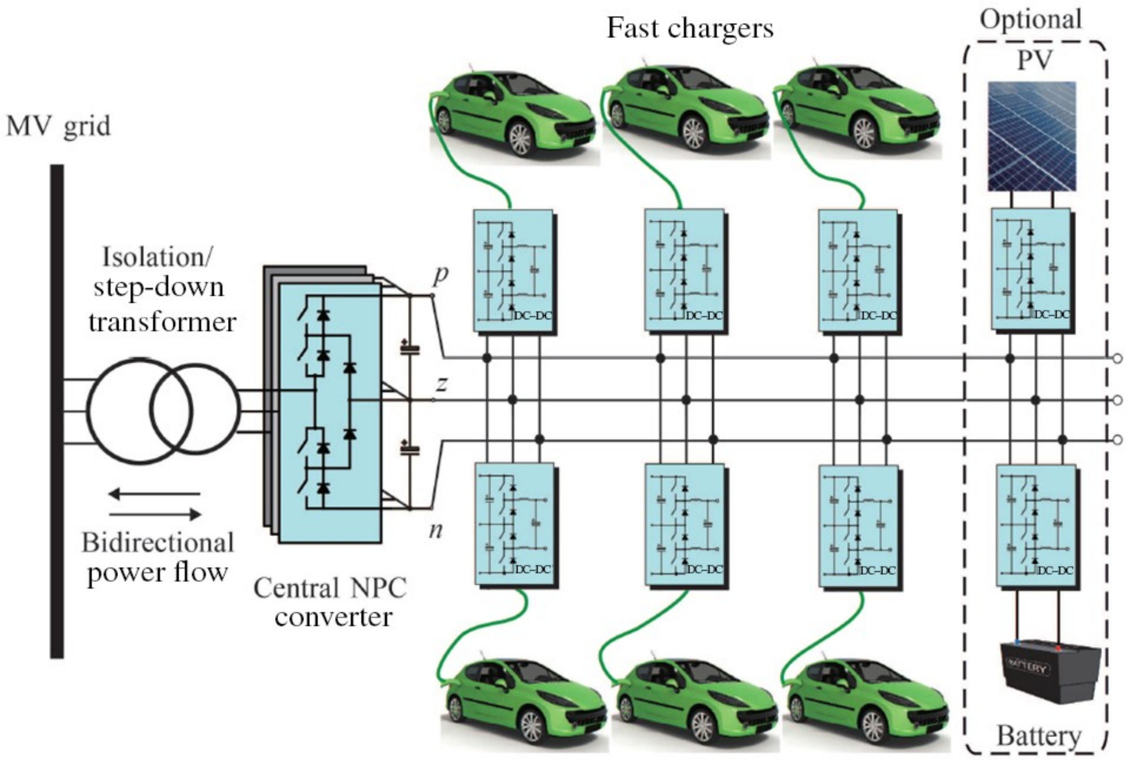

Figure 11. Central DC-link

This idea can be tricky to use as the cars need individual potential and cannot connect directly to one central DC-link as depicted in Figure 11. The vehicles are equipped with sensors that detect earth-fault in the system and that system needs individual potential to each car.

2.4 Transformer

The transformer is necessary in some cases to adjust the voltage but the most important thing is to make the output from the charger unique in terms of potential. It's a security issue that prevents people, that are touching the vehicle, from getting hurt by electricity. The electric system shall not be in contact with the chassis, but if some fault appears that contacts the car to the chassis the transformer secures that there isn't any connection to the grid.

2.5 Earth protection circuits

In the cars there is a special safety circuitry that detects if the equipment in the car is connected to the earth (chassis) of the car. Such a connection could be a hazard for people touching the vehicle and a fault detection results in disconnection of the charging port. See Figure 11. The circuit isn't a part of the charger but it is important to notice that the cars need individual potentials.

The earth fault detection is based on two high valued resistors, R_1 and R_2, that are connected to either the positive or the negative pole of the battery. If for instance the negative pole of the battery has a faulty connection to earth there will be a current when Switch1 is closed.

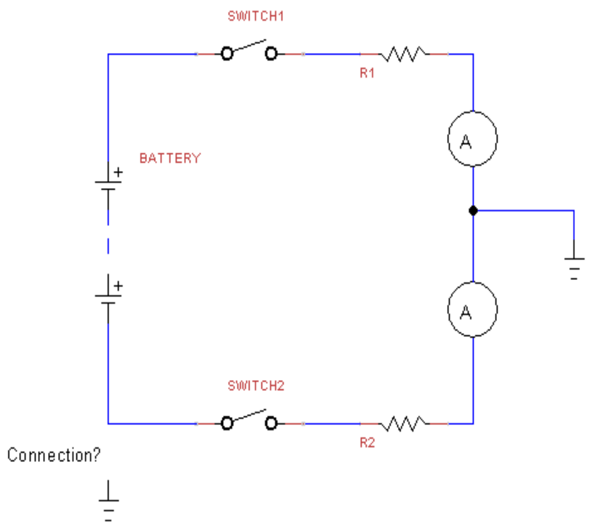

Figure 12. Earth protection circuit.

In order to avoid that the total number of cars should be disconnected, an individual potential is needed for each car, and this potential difference could be taken care of if two capacitors, C_2 and C_3, is connected like in Figure 13. Probably this will be a problem due to current in one of the capacitors and we will need an investigation on this and a standardisation of how it should work.

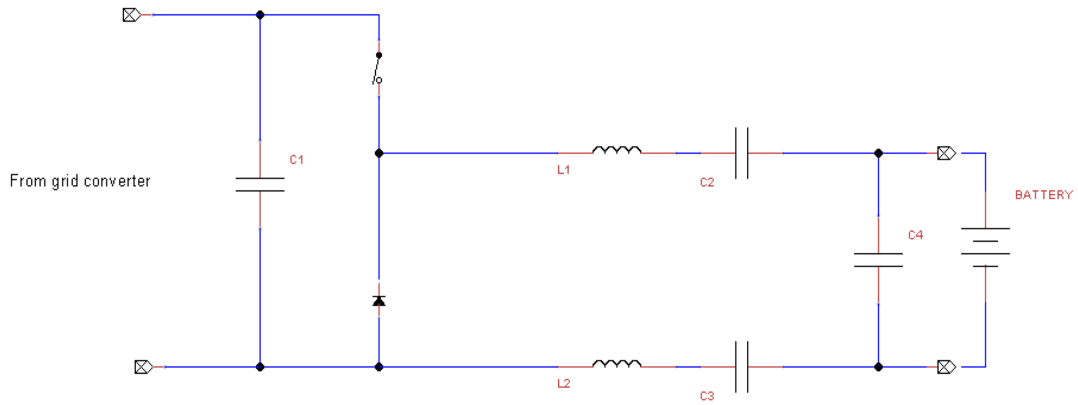

Figure 13. Possible way to share power from a common DC-link

The common DC-link is attractive when we consider batteries or renewable energy sources, so another suggestion that doesn't disturb the earth protection circuit is to rectify the grid voltage to a common DC-link and after that have individual modules with transformers that feed the vehicles. Referring to Figure 9 and 10, the rectifier part and C_1 will be large in that case. The HF-inverter and transformer will be the actual module.

3. Cost and efficiency

The cost is estimated for the main components of a 10, 17 and a 33 kW module. It is estimated that 33 kW is a limit for placing the whole converter on a single PCB. Some calculations on efficiency and temperature are also done. This investigation is concentrated to the DC-DC-converter inside the modules.

3.1 Main components 400Vac / 10 kW

In order to get an idea about the cost of a fast charger the main components are dimensioned and the cost is summarised. The cost is taken from distributors on the internet and using fairly high numbers a good approximation of the cost is found. To my experience the price found in this way can be halved when higher volumes are at hand and the prices can be negotiated.

Main components:

- Transformer made of standard ferrite cores.
- Rectifier 400 V / three phase, sinusoidal current
- DC-link capacitor
- HF-inverter for feeding the transformer
- Inductor
- Active rectifier
- Grid filter
- Control PCB.

A design tool from Ferroxcube, SFDT 2010, is used for the dimensioning of transformer and inductor.

According to Ferroxcube design tool an E 100-core can transform 10 kW at 100 kHz.

Table 1. Transformer data 10 kW, E100-core 3C94

Core Volume	201390 mm^3
Core Area	735 mm^2
400 V Primary	25 turns
Primary resistance	11 mΩ**
Pfe	30 W
Pcu*	20 W

*Assuming equal losses in primary as in secondary

**Litz-wire, copper fill factor of 40 %

Power losses in the converter are calculated from the simulated current, see Figure 14. The result is obtained with a Simscape model using IGBT's on the primary side and on the secondary side silicon diodes rectifies the voltage, the simulated circuit has no resonant capacitor. In the simulation the transformer inductance is 5 µH and an extra 35 µH is placed on the secondary side. The values are referred to the primary side.

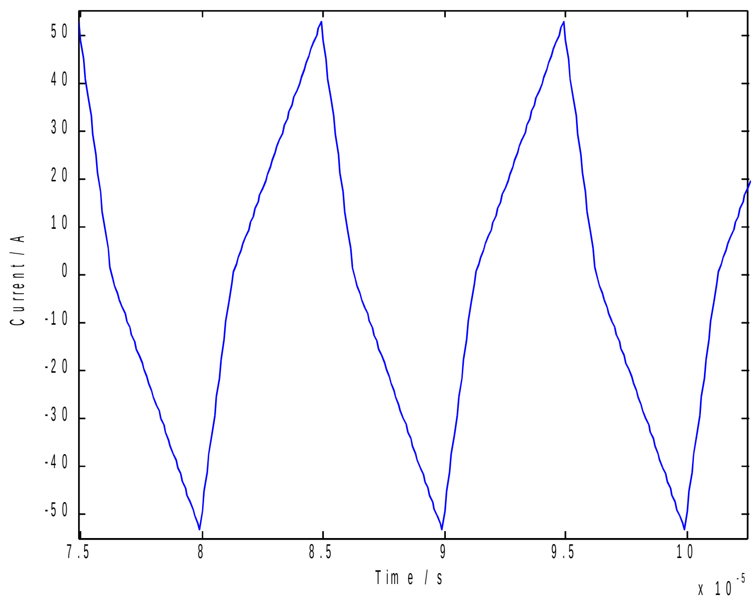

Figure 14. Simulated current, 650 Vdc, inductance 40 uH, Vbatt = 400 V, P=10.6 kW and Irms = 30.7 A.

The simulated current is used for the dimensioning of the SiC transistors and the current behaviour shouldn't differ if the transistor is of SiC type. A ROHM transistor, SCH2080KE is chosen.

Table 2. Inverter to the HF-transformer

Transistor	SCH2080KE
Rdson	80 mΩ
Current	30.7 Arms
Resistance losses	75 W/leg
Eon*	218 uJ
Eoff*	64 uJ

*@ 10 A / 600 V

The switching losses at 100 kHz are calculated to 37.5 W / component but if we can avoid the losses that are related to the turning on of the component the switching losses are reduced to 6 W. The switching losses can be minimised if a resonant link is used. At resonance the current is zero when the components are switched on and off, which isn't the case in Figure 14, but can be achieved if a LLC-converter is used, as in Figure 9.

In the inverter the RMS-current is 31 A and the internal series resistance is R_{dson} = 80 mΩ resulting in a loss of 77 W / phase leg. The total power losses are 231 W and in the rectifier it is 3 * 24 W = 72 W. It's in the same range as in [23] where a 9 kW charger is studied.

An inductor of 35 uH with a peak current ability of 50 A is incorporated in the circuit. It is made using a ETD49 core.

The material cost, i.e. no profit in the last column, for electronics and transformers is found to be 295 Euro . 29 Euro / kW. See Table 3.

Table 3 Cost of components to 10 kW module

Item	Kompon	Numbers	Cost/ Euro	Cost	Sum
SiC	Rohm	14	5	70	70
Mounting		14	0.5	7	3.5
Diod	Rohm	0	3	0	0
Drossel	30 uH	3	15	45	45
Capacitor	Vishay/digi	1	10	10	10
Resonannt cap				0	0
Styrkort		1	100	100	100
				0	0
Transformer 30 Arms				0	0
Core E100		2	12.42	24.84	24.84
				0	0
Wire/kg		1.94	10	19.4	19.4
Bobbin		1	5	5	5
Insulation		1	2	2	2
				0	0
				0	0
Induktor 35 uH / 50 Ap				0	0
Core ETD49		2	1.07	2.14	2.14
Wire/kg		0.2	10	2	2
Isolation		0.5	2	1	1
Bobbin		1		0	0
					10.28
					295.16

If the charger has an efficiency that substantially drops for low power it could be useful to have several modules that switch in when power is needed and they can operate on a high efficiency. In practice it has been shown that a peak efficiency of 95 % for the whole charger is realistic, and that it is possible to have more than 90 % efficency from 10 % of the peak power. In [12] it is reported of an 11 kW charger has a peak efficiency of 98 % and over 94 % from 1 kW and upwards.

If the efficiency varied a lot depending on power level it could be useful to completely shut off modules at low load. Since it's possible to have a high efficiency over a wide range it is not considered as an argument for building smaller modules. It's probably better to make an effort in making bigger modules with a high efficiency. High efficiency comes with increased cost since material is needed and perhaps better grade of core material has to be used. A bigger module will however benefit from lower cost per kW.

It is assumed that it's possible to build the charger module with an efficiency higher than 93 % for power levels of 10-100 % and a peak of 97 % , see Figure 15 which is more or less a replica of the findings in [12].

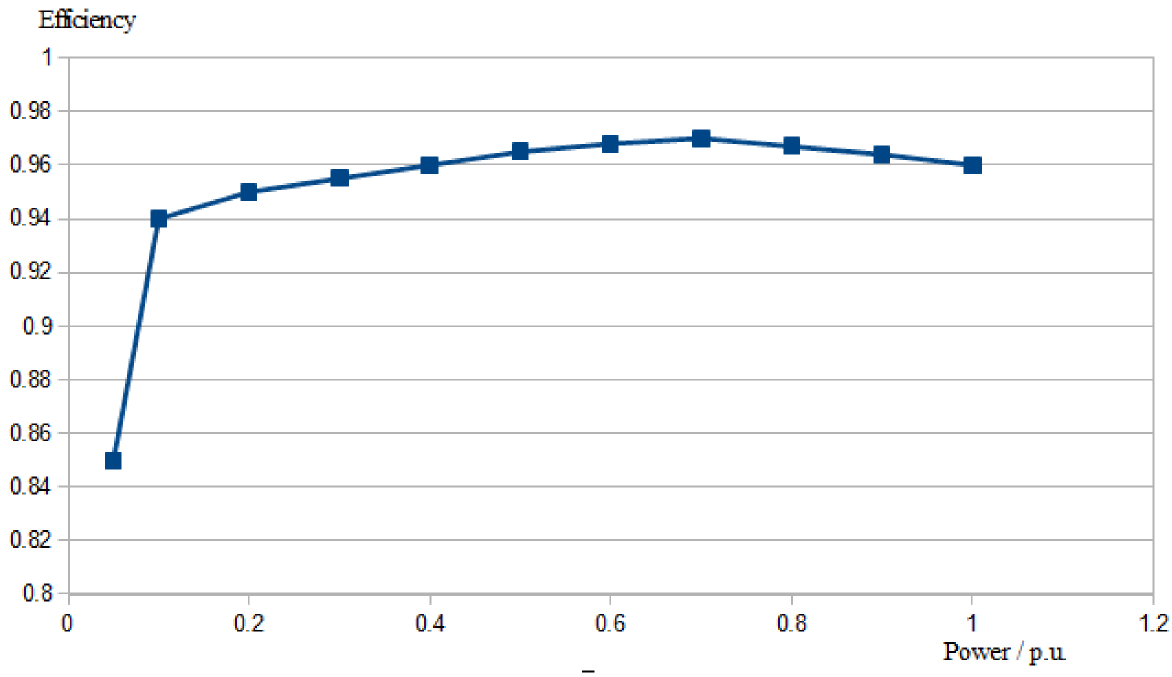

Figure 15. Assumed efficency of the modules used in the investigation.

3.2 Main components 400Vac / 17 kW

In the 17 kW-module, the transformer is made of four pieces of the core E100 and the inductor is made using the core ETD 59. The transistors are upgraded and the CREE-transistor C25M0045170D which have Rdson=45 mΩ is used. There are even better transistors, with Rdson=25 mΩ but as always the high end products are costly. The cost of C25M0045170D are estimated to 6 Euro/piece. This is of course speculative but Si-counterparts cost 1-1.5 Euro and SiC parts will be more expensive to produce due to lower yield and different processes. On the other hand we have alrady seen SiC-parts that outperforms Si even in terms of cost.

Table 4 Cost of components to 17 kW module

Item	Kompon	Antal	Cost/ Euro	Cost	Sum
SiC	Rohm	14	6	84	84
Mounting		14	0.5	7	7
Drossel	30 uH	3	25	75	75
Kapacitanser	Vishay/digi	1	17	17	17
Resonannt kap				0	0
Styrkort		1	100	100	100
				0	0
Transformer 50 A				0	0
Core E100		4	12.42	49.68	49.68
				0	0
Wire/kg		3	10	30	30
Bobbin		1	6	6	6
Isolation		1	2	2	2
Dubbla mtrl-pris				0	0
				0	0
Induktor 21 uH / 85 Ap				0	0
Core ETD59		2	2.7	5.4	5.4
Wire/kg		0.3	10	3	3
Isolation		1	2	2	2
Bobin		1	3	3	3
					384.08

The cost without profit is calculated to 384 Euro, i.e. 23 Euro / kW.

During the spring of 2018 the demand for SiC-components has increased faster than production so the time for delivery have increased and also the cost. For instance the component SCH2080KE have increased in price to 26 Euro and delivery time for large quantaties is after new year. So the prices are today quite volatile and uncertain.

3.3 Main components 400Vac / 33 kW

In this module the power electronics are doubled compared to the 17 kW module and it is assumed the paralleling of the components can be done without problems.

The transformer size is doubled to eight core halves and here one can doubt that the 4 cores in parallel can work without special cooling. Losses are 200 W and the area of the transformer is 6* 0.1 * 0.1 m^2 = 0.06 m^2 and if the surfaces of the transformer are cooled with forced air, α= 25 W/m^2K the temperature rise will be 75 K, which is acceptable but on the limit. So there has to be efforts on the cooling and there will be cost associated with the cooling as well. In Figure 16 the resulting temperature on the surface of the simulated transformer is shown.

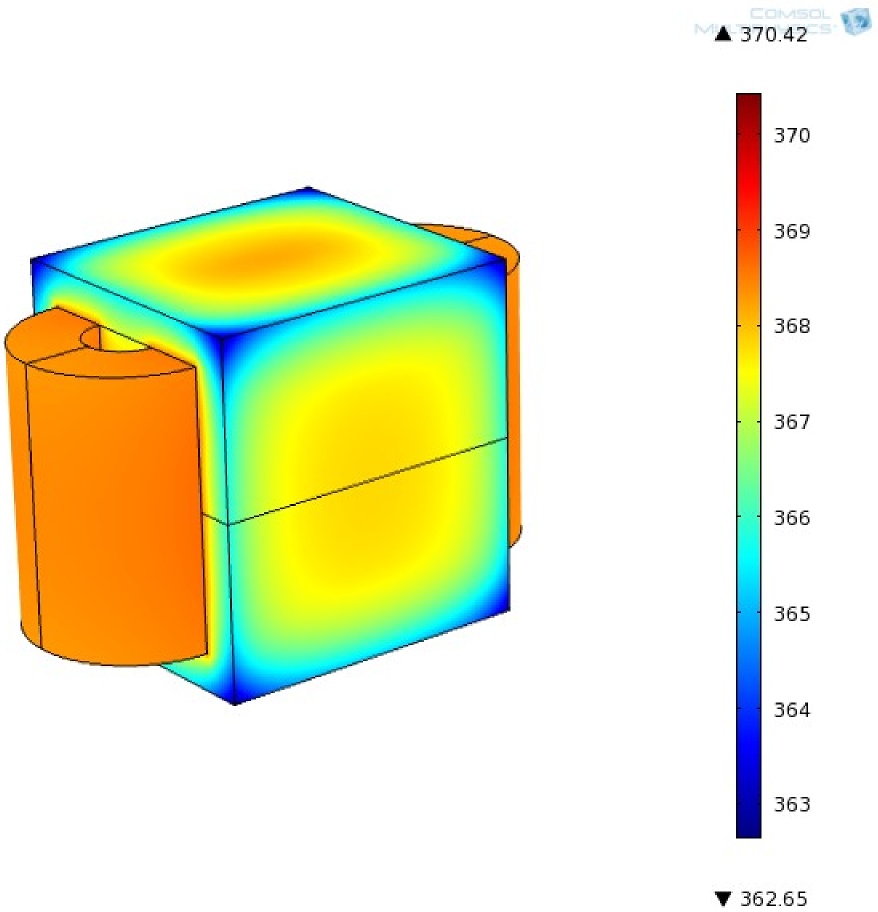

Figure 16. Transformer comsol model, losses 180 W, heat transfer 25 W/m^{2}K

The material cost without profit is calculated to 678 Euro, see Table 5.

Table 5 Cost of components to 33 kW module

Item	Kompon	Antal	Cost/ Euro	Cost	Sum
SiC	Rohm	28	6	168	168
Mounting		28	0.5	14	14
Inductor	30 uH	3	50	150	150
Capacitor	Vishay/digi	2	17	34	34
Resonant cap				0	0
Styrkort		1	120	120	120
				0	0
Transformer 100 A				0	0
Kärna E100		8	12.42	99.36	99.36
				0	0
Wire / kg		6	10	60	60
Bobbin		1	8	8	8
Insulation		2	2	4	4
				0	0
				0	0
Induktor 11 uH / 170 Ap				0	0
Kärna ETD59		4	2.7	10.8	10.8
Wire / kg		0.6	10	6	6
Insulation		2	2	4	4
					0
					678.16

The cost / kW of the different power sizes is shown in Figure 17.

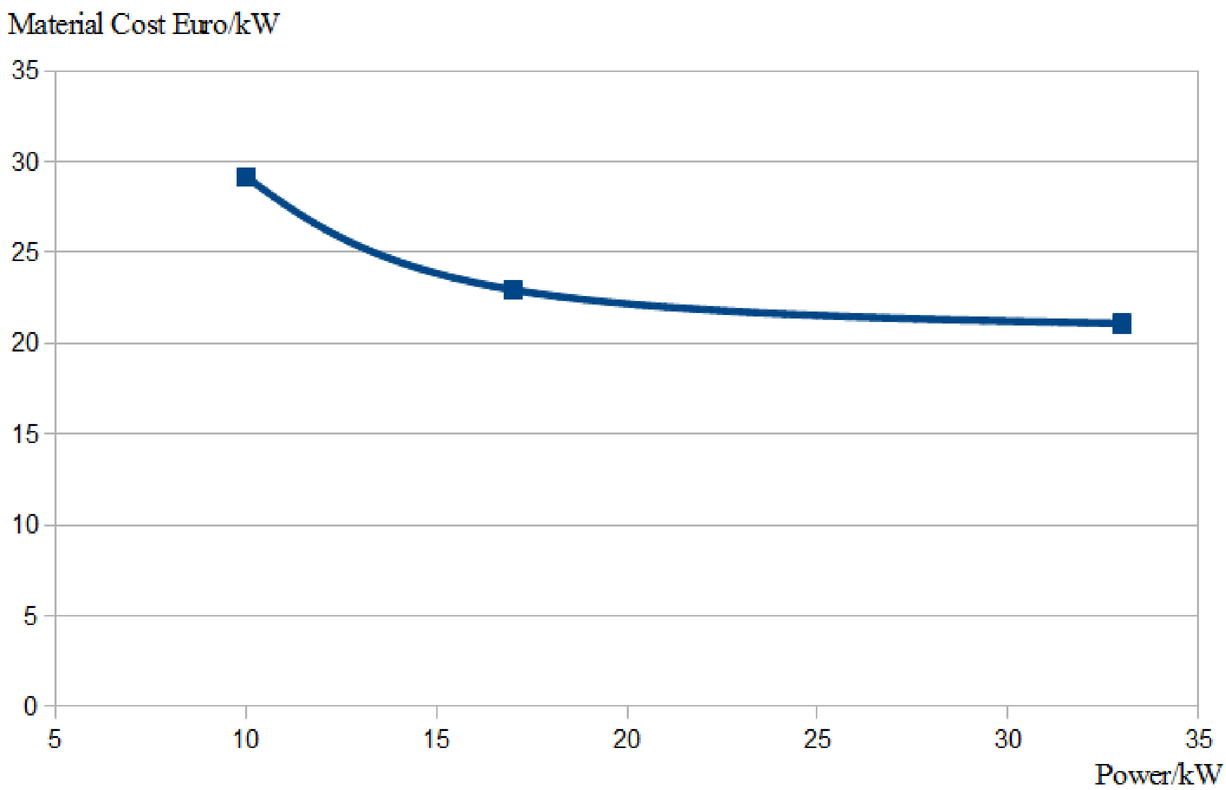

Figure 17. Cost / kW module from simple cost model.

This simple and limited study shows that the material cost per kW are lowered at 17 kW compared to 10 kW-module. i.e. the fixed parts (control board) are a minor part of the cost when the power increase. It would be possible to reach 20 Euro / kW if high volume production is possible, which is interesting to compare to prices for whole chargers that are in the range of 500 Euro / kW. Of course there are displays and communication equipment in the chargers but it should be possible to make it less expensive.

4. Module size investigation

In order to find the optimal module size it's important to know how the cars will be distributed in the future. Some cars will be long range heavy vehicles and some will be smaller 'city'-cars. A plausible way of categorizing the cars may be adjusted to the semi-standard of Europe. Class B and D are skipped, because there are no BEV's in these segments yet. The most interesting class is the C2, where there is a lot of activity this year and next year. This class is used for further calculations.

It's important to notice that battery development is fast and probably will the power levels change in a couple of years.

Table 6. Vehicles on the market within one year

	Battery size	Approximate Range	Peak Charge Power
A eUP,	20-30 kWh	170 km	50 kW
C Leaf, i3*, eGolf	35-43 kWh	270 km	67 kW**
C2 Leaf*, eNiro, Bolt, Model 3, VW ID	55-60 kWh	400 km	100 kW**
E Model S, Audi eTron	95-100 kWh	500 km	150 (350)

* Late 2018 versions of i3, Leaf and Ioniq, Bolt have charge power of 50 kW

** Assumed power level
*** This table was done in 2018 and we know now that i3 and Bolt remain 50 kW, Model 3 can be charged with up to 200 kW. Id3 125 kW

If we go on and assume that one set of modules can charge two cars, the possible charging powers will be:

Table 7. Different charging alternatives, charging power / kW.

	One car	Two cars
A+A	50	100
A+C	50 or 67	117
A+C2	50 or 100	150
A+E	50 or 150	200 (>)
C+C		133
C+C2		167
C+E		217 (>)
C2+C2		200 (>)
C2+E		250
E+E		300

Sorting the possible powers in ascending order,

50,67,100,117,133,150,167,200... / kW

Several of the powersteps is 17 kW and based on that one suggestion is to use a power module of 17 kW. Adding a number of 17 kW-modules can result in the powerlevels seen in Table 6. Another version is to choose 33 kW as a base and for instance a 150 kWcharger could be equipped with three 33 kW modules and three 17 kW which will combine to the actual powers.

One thing to consider is how the charger should react? If two cars arrive at almost the same time should the charger be democratic and share the power equally between the cars or should the first be charged as fast as possible? A possible way is that the car owner notifies to the charger how long time they will rest/eat or just wait for the car. In this way it might be possible that people in real hurry gets the maximum power but also have to pay a little bit more then the average car owner.

4.1 Calculations on an ideal 150 kW charger and a C2-class car

A simulation of an ideal charger that charge two cars where the first gets 100 kW(limited by the battery) and the other car only gets 50 kW until the power to the first car is lowered result in the charge times according to Figure 18, 34 minuts for the first one and 45 minutes for the second one. They arrive almost simultaneously to the charger and one is slightly before the other.

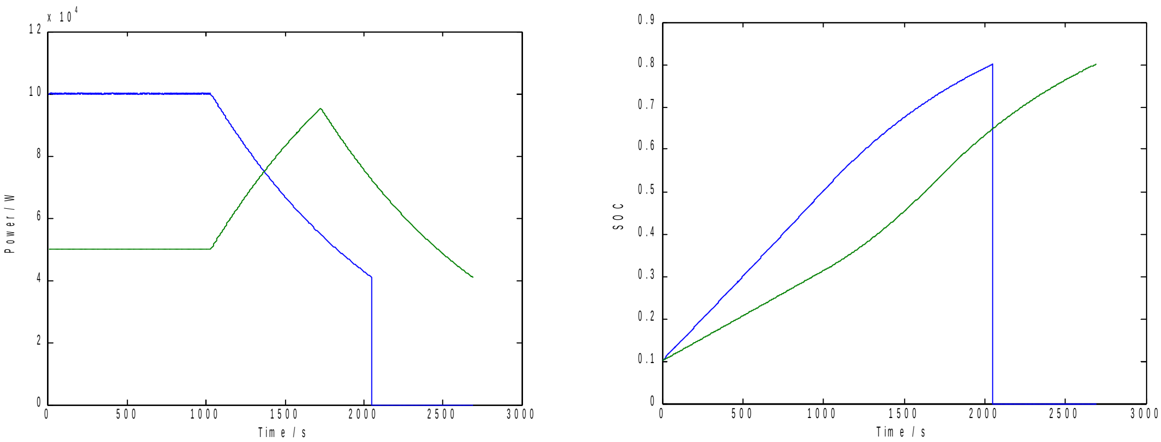

Figure 18. Ideal charger that freely can adapt power between two cars. Blue first charging car and green the second one.

A strategy where the first car gets the maximum power that the battery can absorb and the second car gets the rest of what the charger can deliver seems to be the best alternative in terms of utilisation of the charger. The other alternative is that they share the power equally from the charger and due to the limitation of power during high SOC the overall charging will take longer time. If we sum the two charging times it is slightly higher when they share the power. The difference is only one minute so one can discuss if it's better to share the power.

When having a low amount of modules it's not possible to adapt exactly to the ideal charging behaviour so there will be differences. How well a charger can adapt to different situations is investigated using different number of modules. We start with one big 150 kW module and then two 75 kW-modules and so on.

A car with a battery according to Figure 7 is assumed. The car has a battery of 60 kWh, max charging power of 100 kW. When 50 % of SOC is reached the charging power is falling towards 42 kW at 80 % of SOC. The cars charge between 10 % and 80 % of SOC. The charged energy is 42 kWh and the car have travelled 280 km assuming 15 kWh/100 km at 100 km/h.

We study how a charger of 150 kW behaves, having different number of modules. And we assume that a number of cars arrive at the same time to the charger.

When having one big module the power is limited by the battery to 100 kW and total charging time is 34 minutes, mean power is 83 kW, see Figure 19. If the charger has two modules and two cars are sharing the power, Figure 20, the max power to each car is 75 kW and the charging time is prolonged but the mean power for the whole charger is increased. Charge time is increased to 42 minutes and mean power is 144 kW, i.e. Already with two modules and two vehicles result in a good utilisation of the power from the charger.

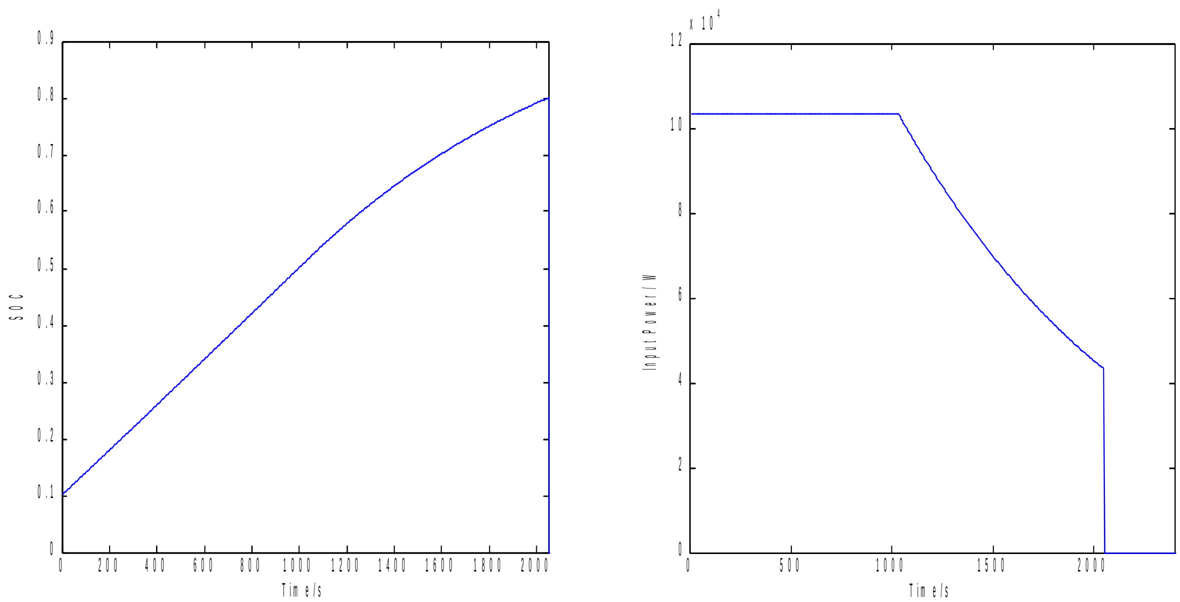

Figure 19. One module and one car

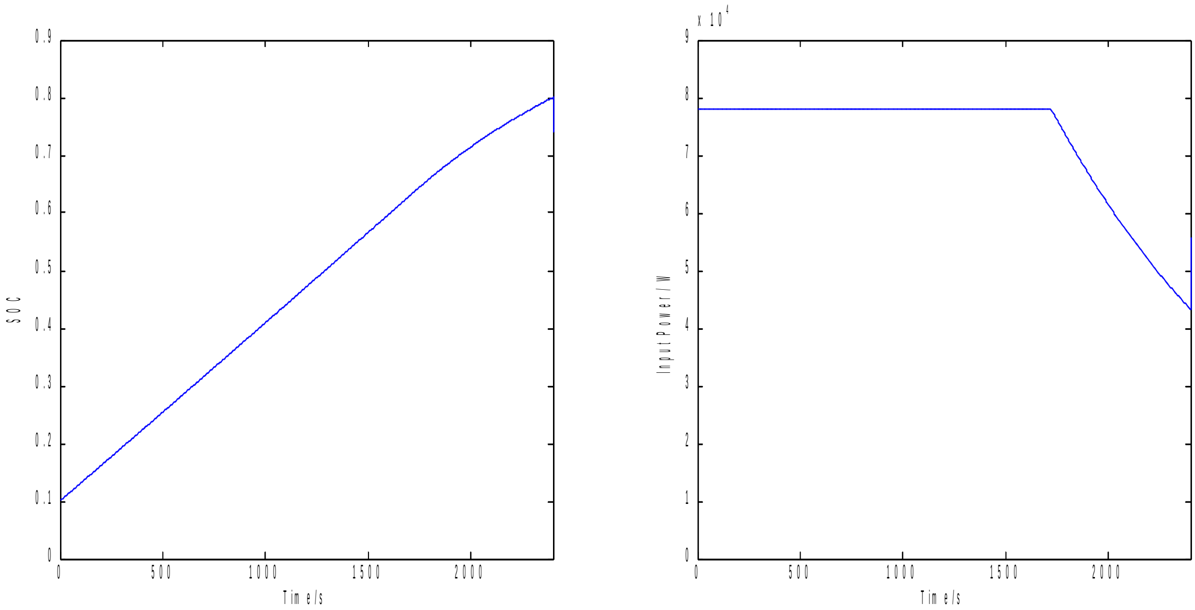

Figure 20. Two modules and two cars, mean power 144 kW. Both cars gets the same power.

If we let the charger have three modules and three charging cars the charge time is 48 minutes. The batteries of this particular car can be charged with 50 kW, i.e. one module per car, almost the whole SOC-range from 10%-80% of SOC. The charger is utilised in a good way but the charging time is rather long.

It is not considered as sensible to use 150 kW for more than three cars. Four cars will need four modules and if max power is 150 kW each car will have 37.5 kW which is rather low as considered as a fast charger. The charge time will increase to more than one hour and this is considered as not good enough.

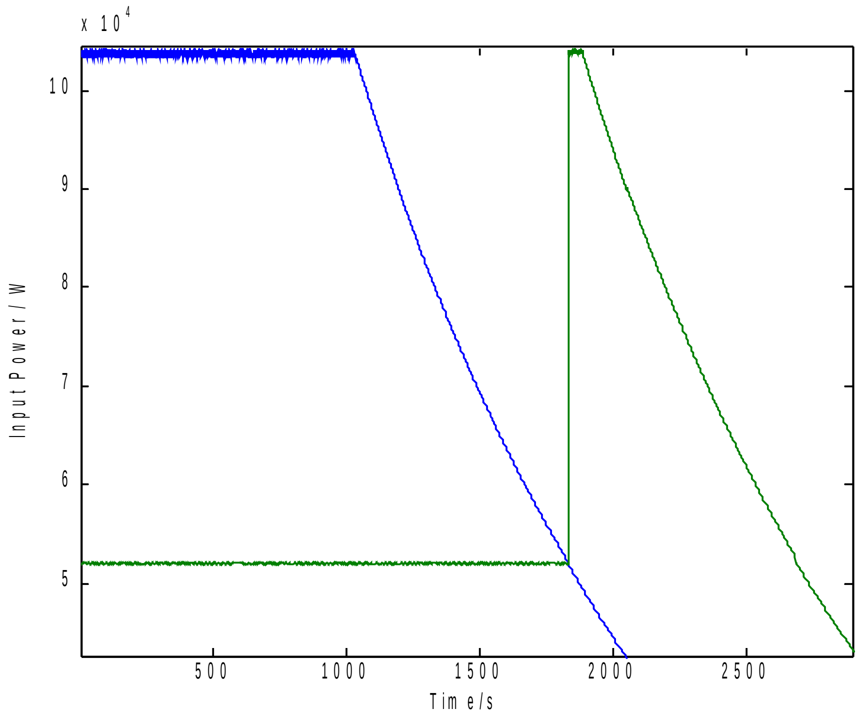

Figure 21. Three modules two cars, mean power 139 kW, blue power of car no. 1, green no. 2.

If two cars are using the charger with three modules, the first vehicle can leave after 34 minutes, i.e. the first arriving car has the same charging time as if the whole charger was used for one car. Simultaneously, the second car is charged with 50 kW until the power to Car no. 1 is lower than 50 kW. Then one module switch from car no 1 to car no 2. There is a big step in the power level and the power adaption isn't that good for the second car. The charge time for the second car is 48 minutes which is quite long.

If the charger has four modules two options are available, the first car can have three modules resulting in 34 minutes but the second car will charge with only 37.5 kW which is lower than with three modules. The low power to the second car results in slower charging compared to the three module alternative. The second alternative is that they get two modules (75 kW) each and the situation is the same as with two modules.

The total charge time for two vehicles with different number of modules is displayed in Figure 22.

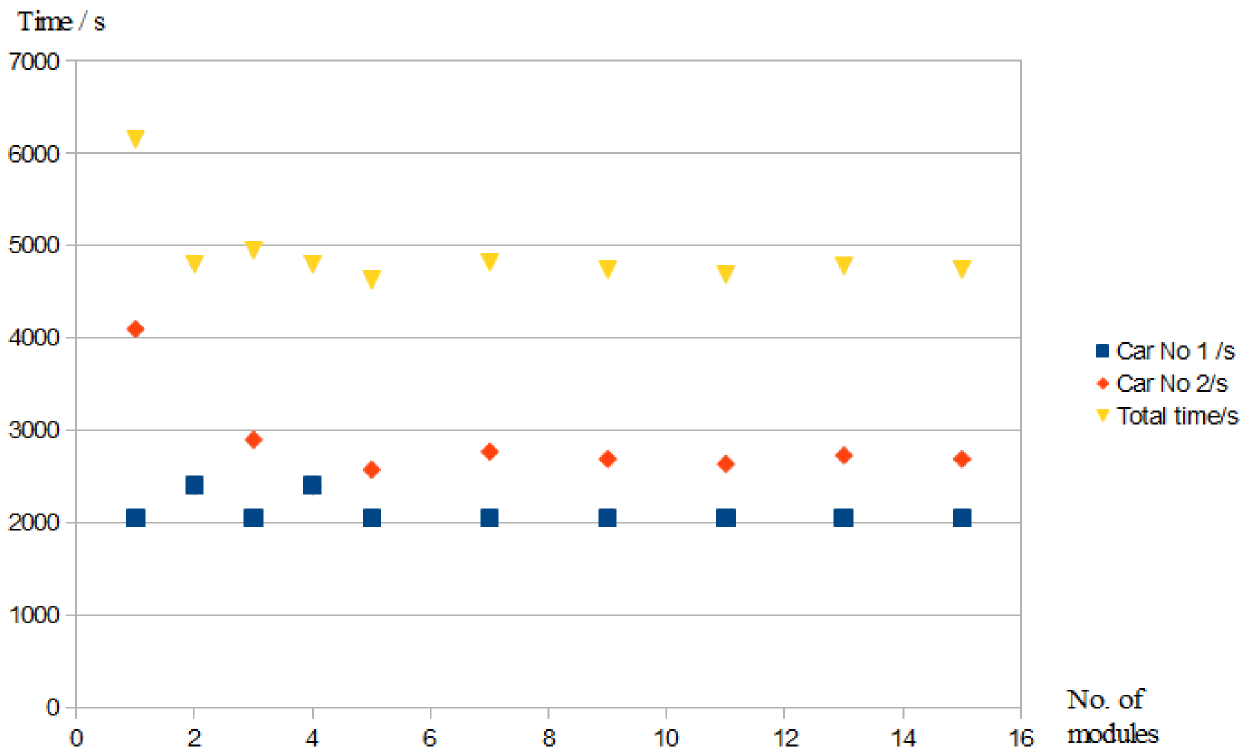

Figure 22. Charge time for different number of modules.

All even numbers of modules can have the result as with two modules. If we compare three modules with the other alternatives, the first car have a charging time of 34 minuts but the second carr may be charged 10 % faster if five modules are used instead of three.

4.2 Calculations on simultaneous charging of two or three vehicles

We can study how the charging behaves if there is a continuous flow of cars arriving to the charger and the time between arrivals is optimal in the sense that no queues are building up and the charger can serve exactly the amount of cars arriving.

First arriving car are prioritised and gets a power limited by the battery. When second car arrives it will get the available power and when first car doesn't need the module(s) it is switched to the second car.

We measure the individual charging time for one car, and the time between arrival of a car. The mean power is a measure how well the charger is utilised.

Table 8. Individual charging time and time between arrivial

	Module size	Charging Time	Mean Power	Arrival Time
1 Module 1 CP*	150 kW	2050 s	83 kW	2050 s
2 Module 2 CP	75 kW	2401 s	145 kW	1200 s
3 Module 3 CP	50 kW	2880 s	155 kW	960 s
3 Module 2 CP	50 kW	2553 s	137 kW	1277 s
4 Module 2 CP	37.5 kW	2401 s	145 kW	1200 s
4 Module 2 CP prioritised	37.5 kW	2565 s	136 kW	1283 s
X Modules 2 CP	Eps kW	2270 s	155 kW	1135 s

*CP - ChargePoint

The last row is an ideal case with infinitesimal modules and with this battery size already two modules are quite close to the ideal case.

How three modules works at steady state is shown in Figure 23.

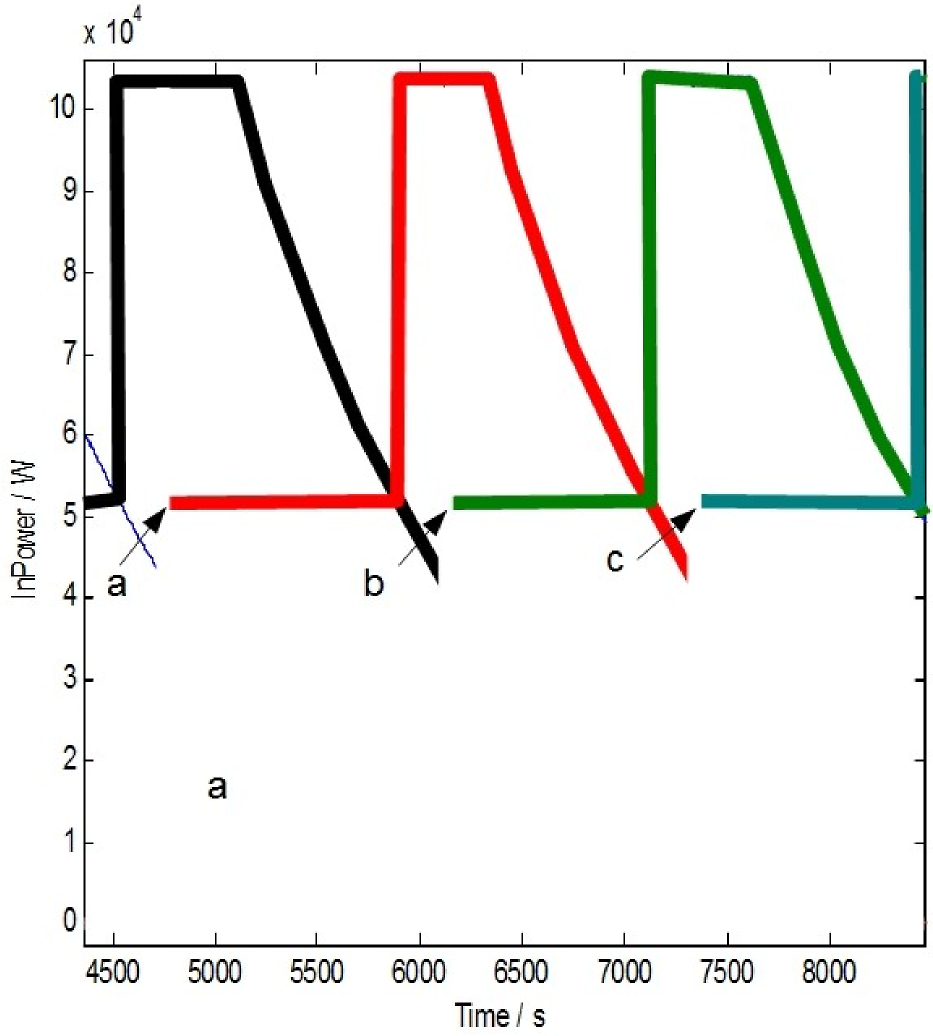

Figure 23. Three modules simultaneously charging two cars time= a denotes arrival of red car, b green car and c blue car.

Charging of two cars, the rows 5 and 6 of Table 8, with four modules can be done in two ways. In the row No. 5 one car is prioritised and gets 100 kW. The other car will in that case only have 37.5 kW and the total time is longer compared to the second row No. 6 where they share the power.

One thought have been that a set of small modules will be more flexible and can adapt to different power demands. But we can see that the average power to the cars is lower and the charging time is longer with four modules compared to three modules. There will be some steps in the behaviour that isn't so good unless we have many modules so the power can adapt more continously. The steps will be depending on the charge power, i.e. it will depend on the battery and on how many cars that can be charged simultaneously. So there isn't any optimal answer to this other than to have as many modules as possible.

What we can observe from this limited study is that one big module isn't so smart. If a charger with one module will charge two cars that arrive at the same time it will take 34 min for the first car but the second will have to wait until the first car is finished and then charge for 34 min i.e. he has to wait for more than an hour.

It will already be better if two modules can serve the both cars and they will finnish after 42 minutes. Then there are other situations in which three modules can be better and of course many small modules give freedom to prioritise in the best way. If the first car is prioritised it's all about the second car, with the assumption of a car with max power of 100 kW it's allways possible to feed 100 kW to the first car (if module numbers are higher than two). The second car can have the rest and for the second car it's more important to get as much as possible.

4.3 Simulations on several vehicles with different battery size

A scenario is investigated where several vhicles arrive to a charger which have two charge points and maximum power of 150 kW. The vehicles are shown in Table 9. The SOC at arrival is 10 % and they leave when the SOC has reached 80 %.

Table 9. Cars arriving to chargers. Fifth column is charging time for the car if there is no limits on the charger side.

Car	Battery Size kWh	Peak Power kW	Charged energy kWh	Time /s
E/SCG	110	150	77	2508
C2/Bettan	75	100	52.5	2565
C/Gunnar	55	67	38.5	2807
C2/Ada	95	100	66.5	3248
A/Leif	36	50	28.8	2462

A test series is set up where the vehicles are arriving with a fixed timing but with randomly found order.

The cars arrive at time=0,1000,2000,4000 and 4500 s but the car size are chosen by means of an assumed car probability curve. It's a Rayleigh distribution with minimum battery size of 22 kWh and the most probable batteries between 40-65 kWh.

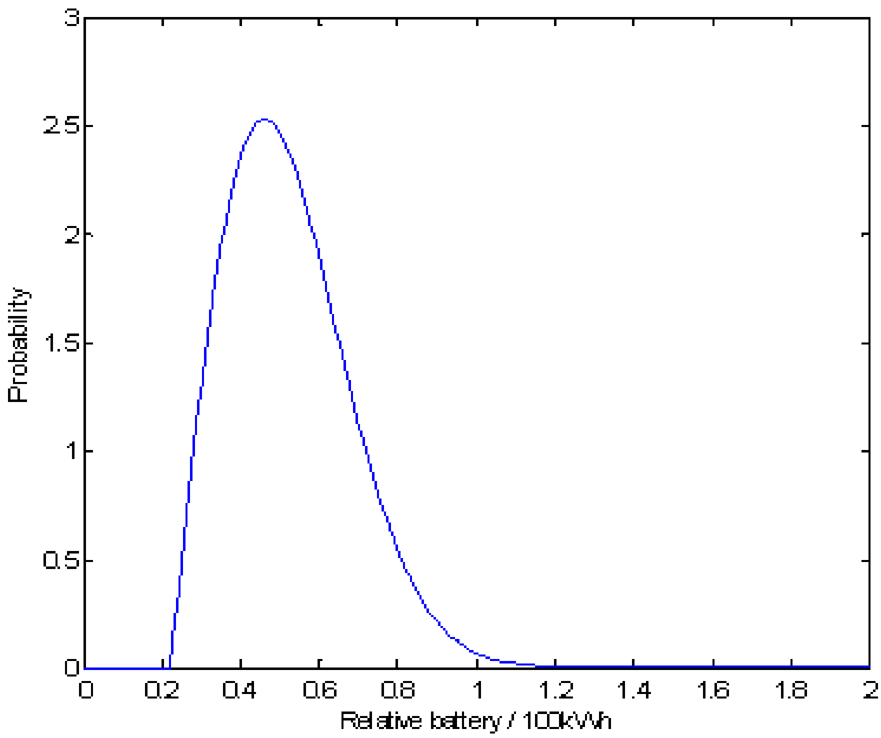

Figure 24. Probability curve of the battery size

Random numbers are found from the Mathlab command ' (raylrnd(0.24)+0.22)*100' which will produce a random battery size and rounded to nearest of 'our' car sizes it is found a random sequence according to Table 10.

Table 10. Test cases with randomly arriving cars. Three last columns are time in second.

Case	0s	1000 s	2000 s	4000 s	4500 s	2 Modules	5 Modules	20 Modules
A	SCG	Bettan	Gunnar	Ada	Leif	8397	8191	7962
B	Gunnar	Leif	Gunnar	Bettan	Ada	9170	9042	8975
C	Leif	Gunnar	Bettan	Bettan	Bettan	8327	8014	7963
D	Bettan	Leif	Leif	Gunnar	Leif	7629	7520	7491
E	Gunnar	Leif	Gunnar	Leif	Leif	8070	8070	8071
F	Ada	Ada	Gunnar	Gunnar	SCG	9420	9131	9029
					Sum	51013	49968	49491

It's not so big difference but some cases show 5 % difference between 2 and 20 modules. A stressed case is also evaluated where the cars arrive with shorter time between the cars. See Table 11 where it is shown that no dramatic changes occur.

Table 11. Stressed case

Case	0s	500 s	1000 s	2000 s	2250 s	2 Modules	5 Modules	20 Modules
A	SCG	Bettan	Gunnar	Ada	Leif	8765	8302	7979
B	Gunnar	Leif	Gunnar	Bettan	Ada	8935	8902	8902
C	Leif	Gunnar	Bettan	Bettan	Bettan	8213	7782	7783
D	Bettan	Leif	Leif	Gunnar	Leif	7775	7569	7502
E	Gunnar	Leif	Gunnar	Leif	Leif	7880	7880	7880
F	Ada	Ada	Gunnar	Gunnar	SCG	9265	9069	8924
					Sum	50833	49604	48970

In this case where queues have been built up there are as much as 10 % difference. If the cars are to be charged with just one modules that charge power is shown in Figure 24.

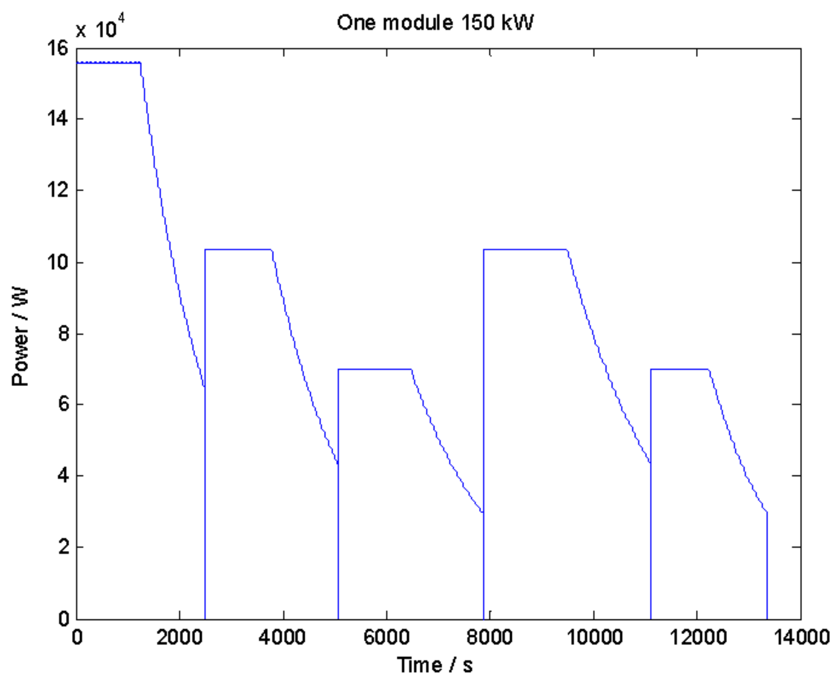

Figure 25. Charging with one 150 kW module, total charge time is three hours 46 minutes .

If there is five modules the charge process can look as in Figure 26 where five modules are used. The charge times are simulated with the program in Appendix B .

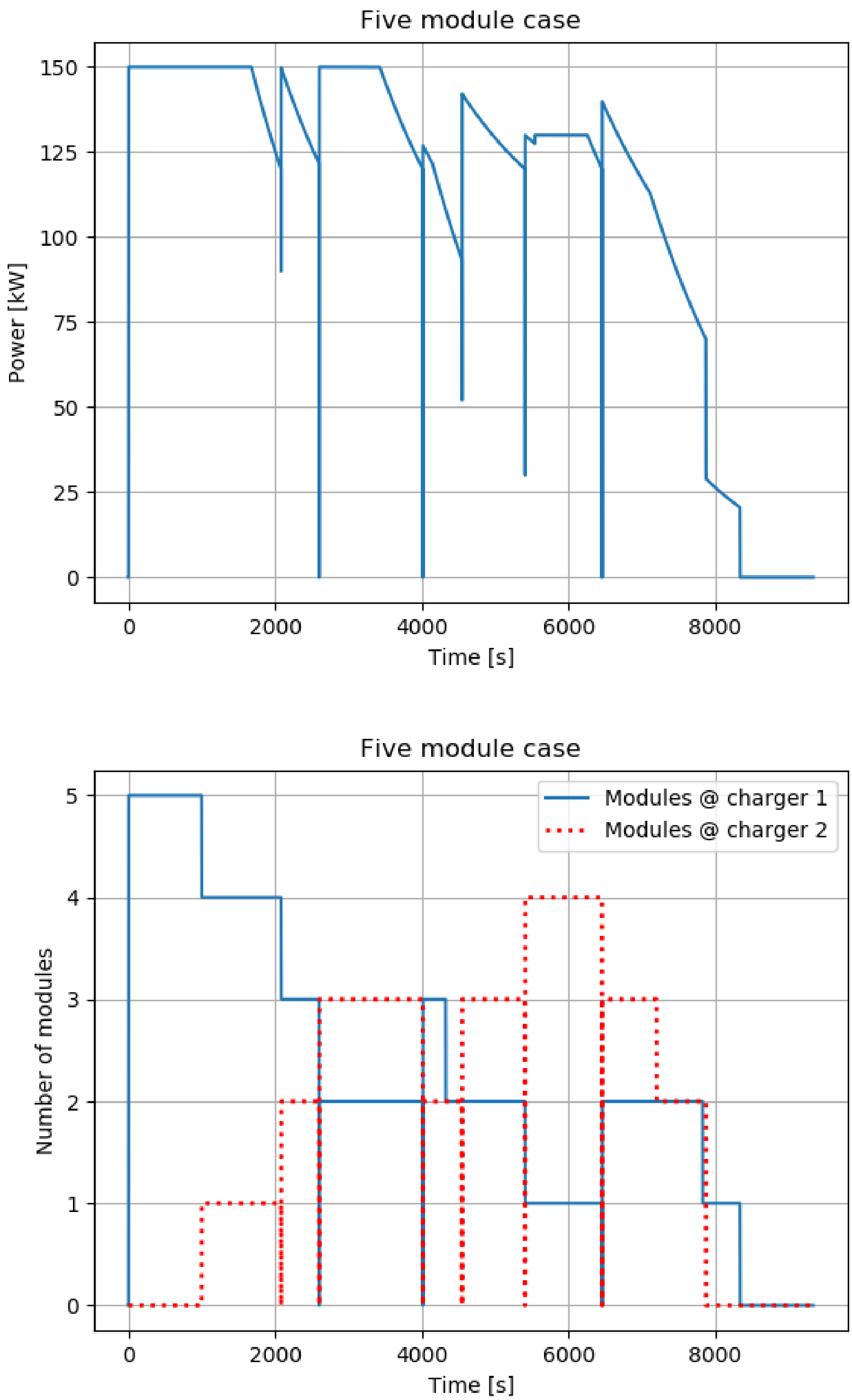

Figure 26. The power to the chargers and the number of modules connected to Chargepoint 1 (blue) and Chargepoint 2 (red dotted).

5. Medium voltage connected fast charger

Normally a fast charger is connected to the 400 V grid, but there could be benefits if the fast charger is connected directly to the voltage level above that. The low voltage transformer, in Figure 27, and the losses associated with the transformer are omitted.

When connecting to 10-40 kV, which is a high voltage compared to the component voltage capability and some action to increase it has to take place. The components can be connected in series but in that case they have to switch exactly at the same time. Another option is to use special converter types that divide the incoming voltage.

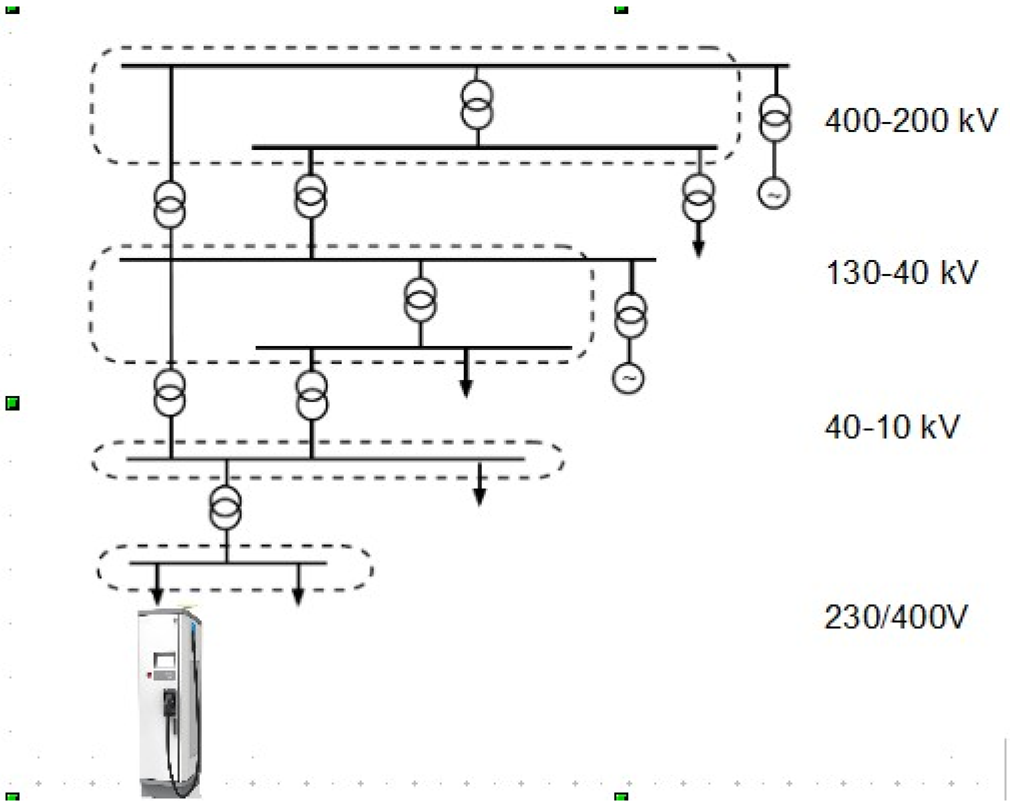

Figure 27. Different voltage levels of Swedish grid.

Medium voltage connection has been studied by Srdic et.al. [5], where the fast charger is connected to 2.4 kV. A similar work on high voltage transformers have been performed by Bahmani et.al, [6], but for wind power application. The transformer is fed by a Dual Active Bridge, (DAB), which also have been used by Haghbin in, [7]. The work by Haghbin has been focused on a fast charger with dual power direction capability.

Depending on the voltage level there are different solutions for management of the voltage. If the switching components have high enough voltage it might be useful with a NPC-connection, see

Figure 27.

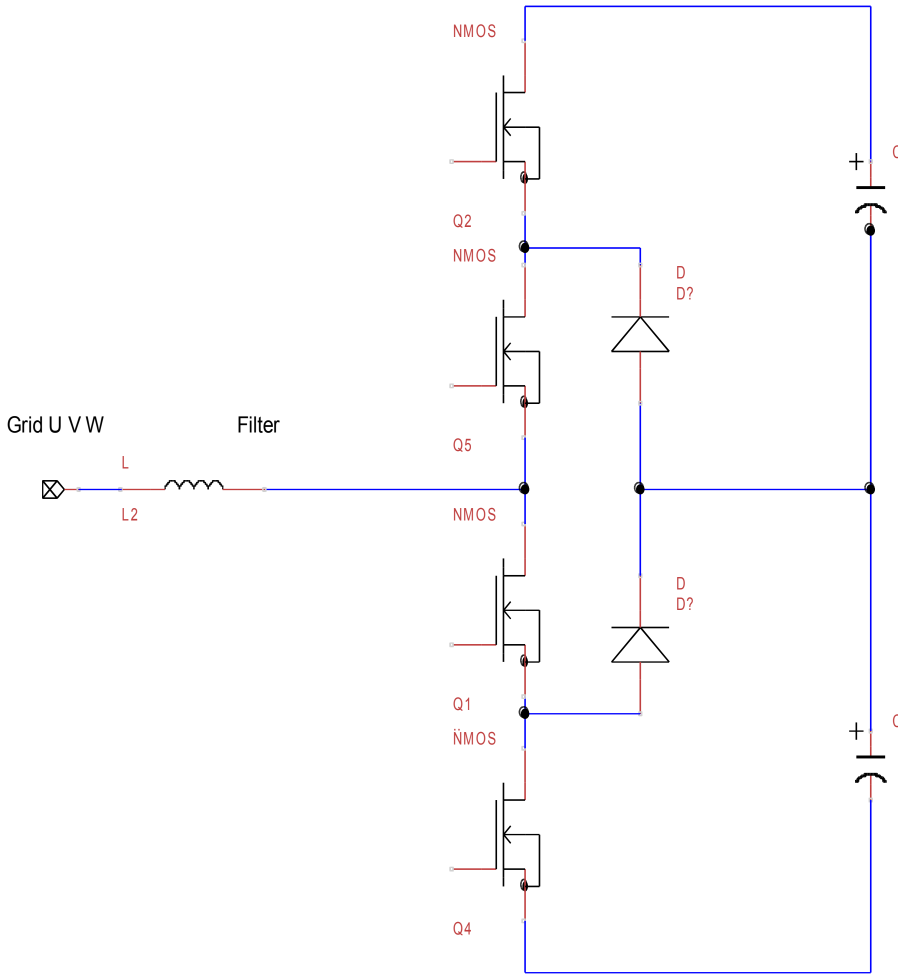

Figure 28. NPC-connection of the grid converter.

If the voltage is higher, Lim et.al., [8], shows how a set of series connected 1.3 kV-converters may be series connected and forming a converter that can handle 13.2 kV. Tripathi et.al., [9] have studied a DAB with SiC based IGBT's and as well as in [7] the DAB-structure makes it possible to feed power in two directions.

5.1 MMC-converter

The operation of this kind of converter has been investigated by Josefsson, [15]. The switching-frequency can be low which makes it possible both to use IGBT's as well as SiC mosfets. The beauty of this type of converter is that the voltage is built up as a sum of modules with a lower voltage. The result is a stepwise voltage and the switching only occurs when we need to add the voltage from one or two modules.

A quick and approximative dimensioning of the circuit says that the maximum phase voltage is 14 kV when feeding voltage is 10 kV. If we assume 12 modules / phase the individual smaller DC-links will have a voltage of 1.2 kV and a SiC component of 1700 V could be used. For instance the CREE component C2M0045170D or SCT3022KLHR from Rohm can handle currents up to 70 A. The current to the transformer is 28 A so this could be handled with this type of component.

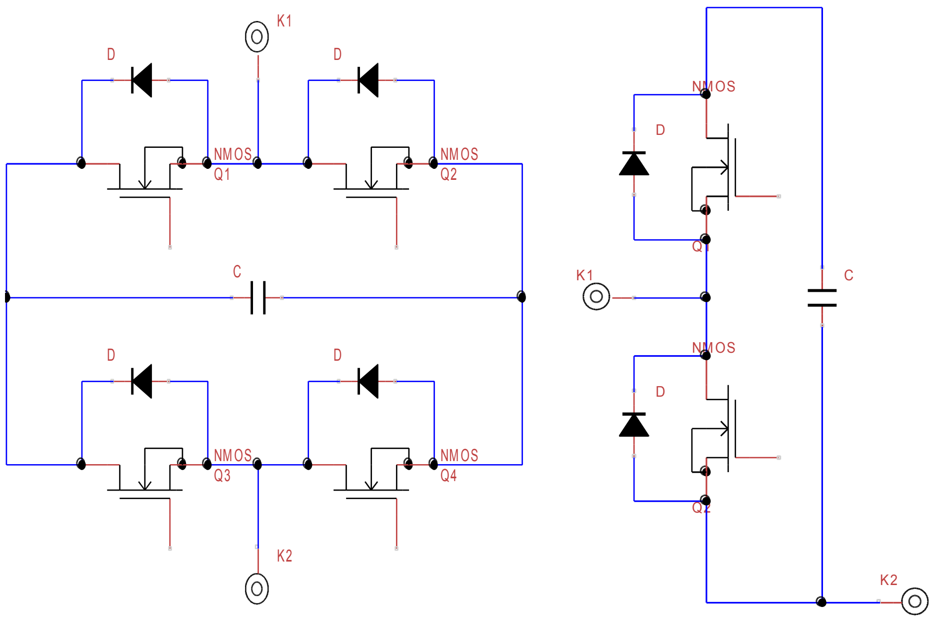

Figure 29. a)Full bridge MMC and b) half bridge MMC

In Figure 29, the module is depicted and positive voltage to the circuit is applied when Q1 and Q4 are on. Negative voltage is applied when Q2 and Q3 are on. Zero voltage can also be applied, when Q1 and Q3 are on (as well as Q2 and Q4). The second figure is a variant with half bridge which cannot reverse the voltage, but have only two components and are simpler.

If we compare this technique with the module in Table 4 and 5 we have to add two big electrolyte capacitors that can handle the discontinous energy flow. The module is only in connection to the grid for a short time during half a period, which means that the current is high and the amount of stored energy cannot be disregarded. Depending on the voltage it can be costly to transmitt gate-signals to the primary side, opto-couplers with high voltage cost 6 Euro at 20 kV which might not be enough. An opto-coupler for 50 kV costs 39 Euro so this can be a real problem. Alltogether it comes as a cost penalty of 50-300 Euros/module and also the transformer has to be constructed with high voltage insulation.

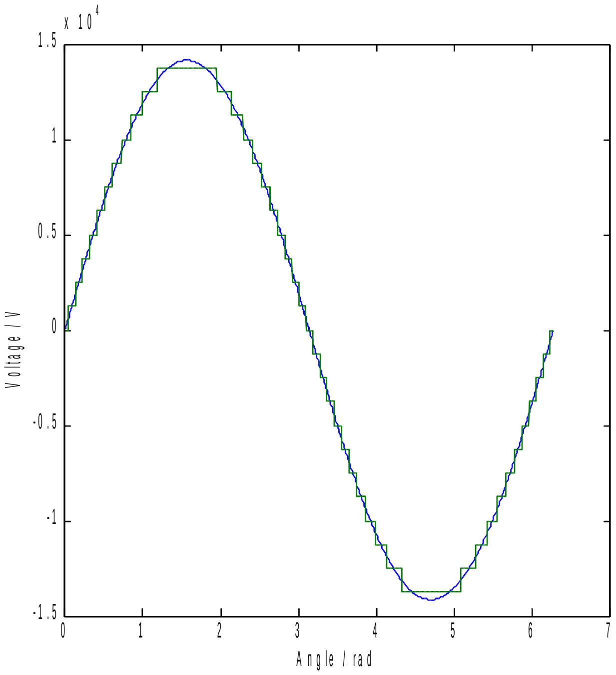

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Figure 30. Resulting voltage from 12 full bridge MMC-modules.

The resulting voltage from a converter based on 12 modules with the voltage of 1.25 kV is shown in Figure 30. The modulation is the simplest possible with no PWM-activity. One important issue with this type of converter is to have voltage balancing of each module.

The converter have been investigated and is currently used in HVDC (High Voltage DC-transmission lines) facilities, [24].

Vasilidiotis, [25], suggests this solution for fast chargers and suggests a distributed battery system. Each module will have a part of the battery pack that otherwise could be connected to a central DC-link. The conclusion from Josefsson, [15], was however that a distributed battery pack will stress the cells more than in an ordinary battery pack.

The voltage between primary and secondary side is high so the transformer has to have thick insulation between the windings. Communication between the primary and secondary side has to be done with high voltage components which are costly. Optocoupler that can withstand 20 kV cost 6 Euro and if the voltage is higher for instance a 50 kV optocoupler costs 39 Euro. The mechanical layout of the module should have one high voltage side separated and insulated as shown in Figure 31.

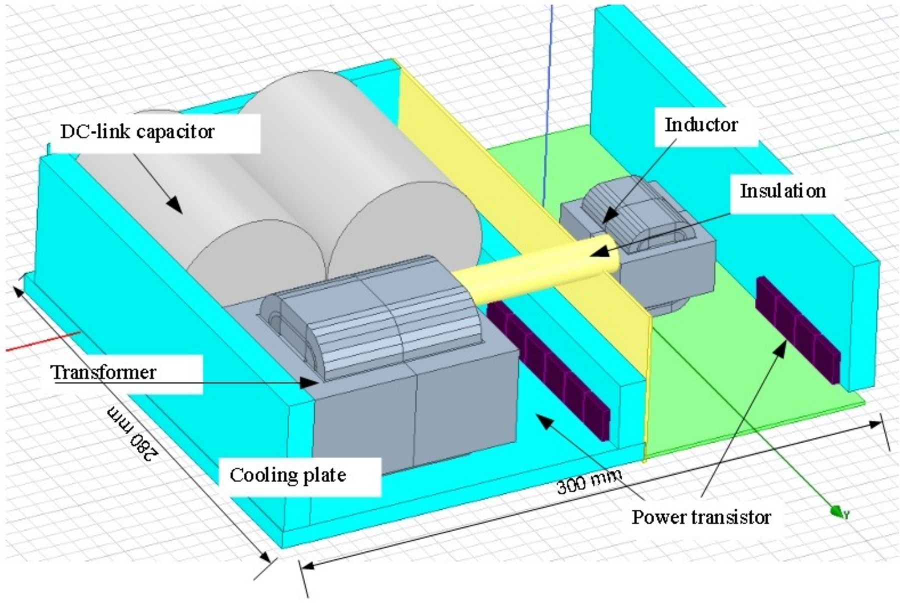

Figure 31. Outline of a MMC voltage. Yellow indicates insulation.

5.2 DAB-converter

An ongoing work at Chalmers investigates high voltage conversion using DAB (dual active bridge), Babak [17]. The main problem today is to handle the voltage on the high voltage side, perhaps this will be solved with new components in the future but for the time being the best available components are IGBT's with a voltage rating of 6.5 kV, which is to low for a 6-pulse connection and 10 kV's. But if it's connected in an NPC arrangement or similar it could be useful for 10 kV-connection.

The IGBT's have rather high switching losses which limit the frequency of such converter.

5.3 Suggested high voltage module based on MMC and DAB

Beside the solution with a big central DC-link and a three level boost converter the MMC-module could be an alternative. Depending which feature is most important we have to chose between a central DC-link where batteries could easily be connected or a solution that can be done without the 50 Hz transformer.

We can place the battery connected to each MMC-module, [15], which could of course be a solution. An economic solution can be made with SiC-components and haveing a voltage of around 1 kV. The transformers has to have good insulation between primary and secondary side. The insulation has to cope with full voltage on the primary side.

The insulation can be made with one or three phase DAB-converter, [7].

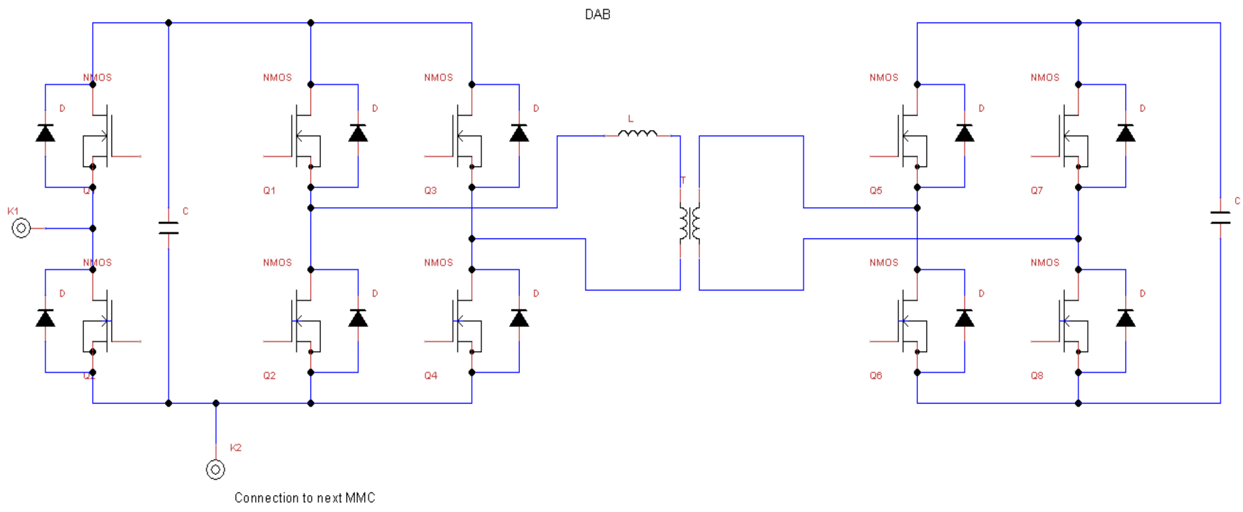

Figure 32. Half bridge MMC-converter module connected to a DAB-converter on each level.

Udc1: DC-link voltage on primary side

Udc2: DC-link voltage on secondary side

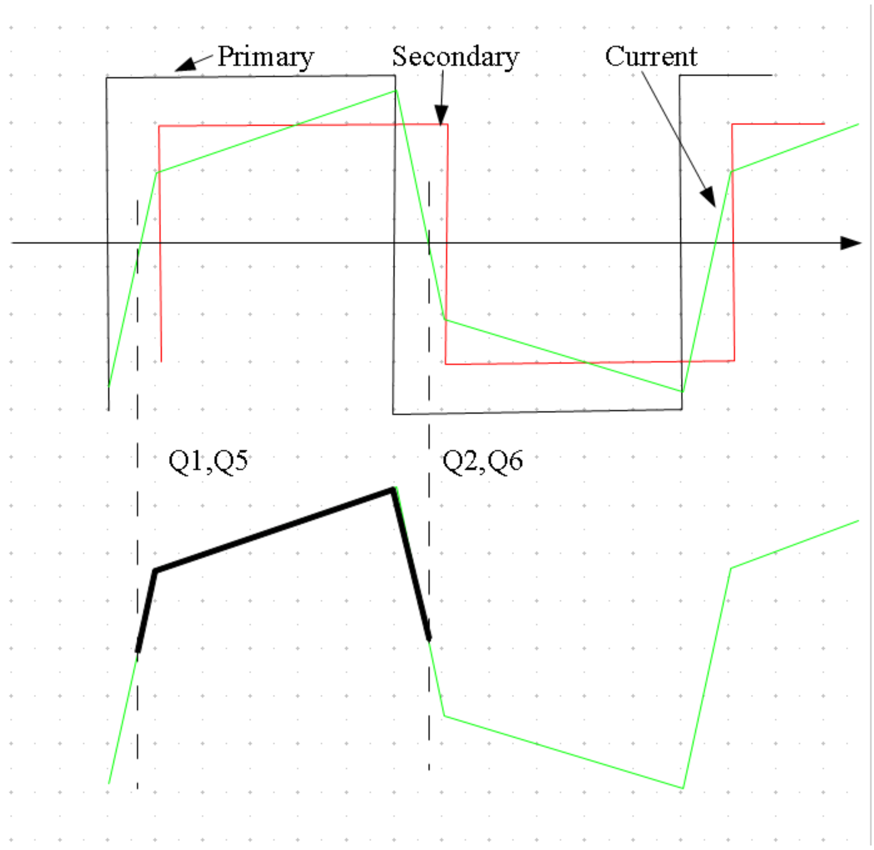

Figure 33. Working principle of DAB, maximum output from primary side

The transformer shall be winded in such way that minimum voltage on the primary side can support maximum voltage on the secondary side. The primary side voltage can then be controlled with a shorter pulse of Q1.

6. Conclusion

In this report a litterature study has been made and ongoing work on different chargers and technique for conversion are summarised.

Regarding the module-size it's clear that several modules in a charger are useful. The charger power is utilised in a better way if several modules can be connected when needed. When charging two cars of the same size at the same time, two modules is very much better than just one and with more modules the charging time is decreased by up to 5 %. More modules give more flexiblity that can be used if the cars don't arrive at the same time. A scenario where the first car is prioritised makes it more important for the second car that there is surplus power that can be distributed to the second car. The charging time doesn't differ so much for the first car but the second car may decrease the charging time with as much as 10 % if there five modules instead of three.

The simulation on several randomly sized cars results in similar figures. Two modules and two charge points is better than just one module. The total charge time is reduced with two modules by approximately 40 % and a further increase of the number of modules will result in a 5 % better charging time.

In the case of 400 V connection 17 kW could be a suitable power level, one power electronic device in each position can handle the power level and the whole converter may be built on PCB's. At this power level the cost of control circuits are quite small compared to the power electronic parts and an assumed distribution of cars with charge powers of 50, 67, 100 kWh, could well adapt to a 17 kW-module. If a battery shall be connected to the charger station a big grid converter that feeds a DC-link can be useful. The battery can easily be connected to the DC-link and from the DC-link several modules feed energy to the cars.

A possible way is to connect the charger modules directly to medium voltage and the 50 Hz-transformerr can be canceled from the system. A mmc-converter is suggested which could be a base for the modules. There are some challenges with high voltage signals to the primary side and also build a high voltage transformer. The cost of the module will increase and it has to be related to the spared cost of the 50 Hz transformer. There are no easy way to connect renewable energy or a battery to this type of converter.

7. Future work

A study that should be performed is to assume the arrival of the cars as a poisson process and make longer simulations on the chargers, and the algorithm that controls the charger.

Medium voltage connection to the grid and a common DC-link is attractive, but not so easy to combine.

If the fast chargers shall connect to medium voltage it is suggested that the MMC-concept is evaluated. From each MMC-module an insulated HF-transformer can produce the module power to the charging of the battery. There will be interesting topics with high voltage, fault handling and control of the MMC-modules.

A common DC-link that are created from rectified low voltage is attractive when renewable energy and/or energy storage are at hand. The energy flow can easily be controlled in the DC-link. A study more concentrated to big grid converters and energy handling could be of interest.

Cost-optimised power conversion and it is suggested that a module of 10 or 17 kW is evaluated. Attractive technique for the conversion is resonant converters and high frequency. Perhaps up to 200 kHz if SiC components could be used. The charging station hasn't any big constrains on the size or weight of the converter. This means that the economics will decide which is the best solution and an optimised solution could be found.

How charging interacts with the grid is an important issue and on the component level an on-board charger that can handle double power direction can be useful in the future. That is beside this topic but another way of handling it is to use a DC-charger of 11-22 kW that connects to the battery and can handle the double power direction. Such a module could be a base for mass production. Perhaps with smaller modification it could be used as a module in fast chargers. And at home or work it could help the grid with V2G and stabilise renewable energy flow.

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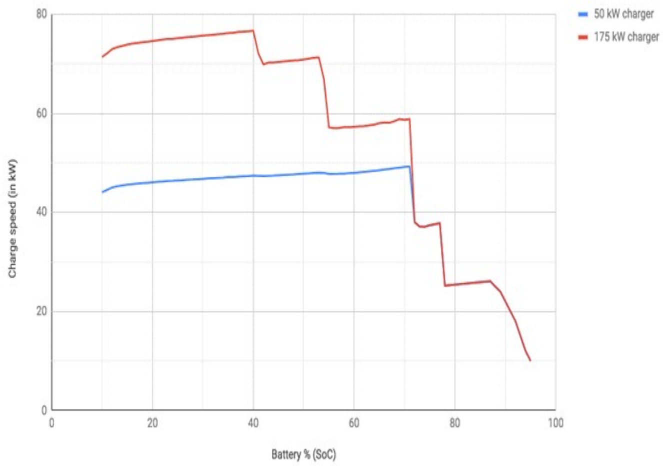
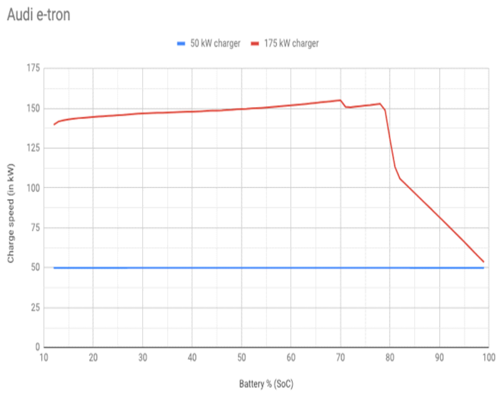
Appendix A. Charge curves

A. Gathered charge curve



Kia eNiro



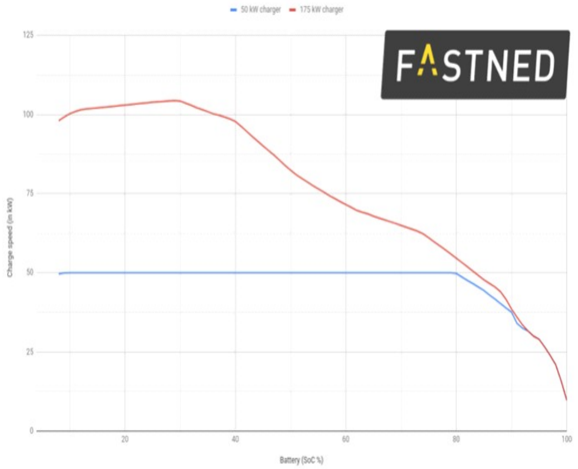
Audi eTron

https://www.greencarreports.com/news/1121426_tesla-model-3-could-charge-faster-in-europe-charging-network-results-suggest

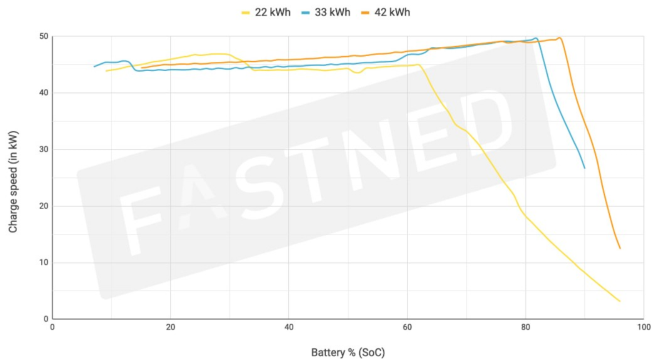
125 kW up to 50 % and then 50 kW at 80 %.

Tesla Model 3.

A software update will be available soon for the I-PACE to enable fast charging up to 100 kW. Please check with your Jaguar dealer for more information.



BMW i3



Tesla Model 3   and BMW i3

Appendix B. Simulation program

```
# Simulation of charge process ################################
##########################################################
# Verkningsgrad oanvänd just nu
# Förbättringar, verkningsgrad, textfil för olika batterityper
# Randomisering av ankomsttid och start-SOC
##########################################################
from numpy.random import poisson
from math import sqrt, ceil
from matplotlib import pyplot as plt
import numpy as np
from queue import Queue

eta = [0.85,0.94,0.95,0.955,0.96,0.965,0.968,0.97,0.967,0.964,0.96]
NUMBER_MODULES = 5
MODULE_POWER = (150/NUMBER_MODULES)*1e3                   #kWH
LADDMIN = 2*MODULE_POWER
TIMESTEP = 1   #second

class Car:
        def __init__(self, time_of_arrival: int, b_size: int = 75, r_b: float = 0.195, max_p: int = 100, name: str = ""):
                self.soc = 0.1
                # self.soc = poisson(12) / 100                             #State of charge is drawn randomly from a
poisson distribution centered around 12% soc.
                self.battery_size = b_size*3600*1e3            #kWH -> [kJ]
                self.power_available = 0 #KW
                self.modules = 0
                self.max_power = max_p*1e3        # [kW]
                self.r_batt = r_b
                self.state = 1
                self.soc_overtime = []
                self.name = name
                self.t0 = time_of_arrival
                self.desired_soc = 0.8
                # self.desired_soc = min(poisson(80,1)[0] / 100, 100)
                return

        def lose_module(self):
                self.modules -= 1
                self.power_available = self.modules*MODULE_POWER

        def receive_module(self):
                self.modules += 1
                self.power_available = self.modules*MODULE_POWER

                #ask if car is happy with amount of juice.
        def get_state(self):
                return self.state

        def get_data(self):
                return {'SOC': self.soc_overtime, 'NAME': self.name, 'T0': self.t0, 'TITLE': "Battery size: {}
MWH".format(self.battery_size//(3600e3))}

        def update_state(self):
                u_batt = 300 + self.soc*100
                i_max = (400-u_batt)/self.r_batt
                desired_power = min(400*i_max, self.max_power)
                desired_modules = ceil(desired_power/MODULE_POWER)
```

```
		s = desired_modules - self.modules
		# print(s)
		if s == 0:			#car happy
			self.state = 0
		elif s > 0:			#car wants more modules
			self.state = 1
		else:				#car got modules to spare
			self.state = -1

		max_power_actual = min(self.power_available, desired_power)
		i_ladd = min(i_max, sqrt((u_batt*0.5 / self.r_batt)**2 + max_power_actual / self.r_batt) - u_batt*0.5 /
self.r_batt)
		w_ladd = i_ladd*u_batt*TIMESTEP
		p_ladd = i_ladd*(u_batt + self.r_batt*i_ladd)
		self.soc += w_ladd / self.battery_size
		self.soc_overtime.append(self.soc)
		return p_ladd

	def is_fully_charged(self):
		return self.soc > self.desired_soc

class Supervisor():
	def __init__(self, number_modules: int = 5):
		self.cars = []
		self.car_queue = Queue()
		self.t = 0
		self.modules = number_modules
		# self.module_array = np.ones(number_modules, dtype = np.int8)
		self.module_uptime = []
		self.car_data = []
		self.out_power = []

	def new_car(self, car):
		if len(self.cars) < 2:
			print(car.name, " has started charging at {} o'clock.".format(self.t))
			if not self.modules:
				c1 = self.cars[0]
				c1.lose_module()
			else:
				self.modules -= 1
			car.receive_module()
			self.cars.append(car)

		else:
			self.car_queue.put(car)

	def remove_car(self, car):
		print(car.name, " has left the station with {0:.2f} % SOC".format(100*car.soc))
		self.cars.remove(car)
		if not self.car_queue.empty():
			c = self.car_queue.get()
			print(c.name, " has joined from the queue.")
			self.new_car(c)

	def supervise(self):
		self.t += 1
		utpov = 0
		state_array = []
		for car in self.cars:
			charge_state = car.get_state()

			if charge_state == -1 and self.modules < NUMBER_MODULES:
				self.modules += 1
```

```
                car.lose_module()
            elif charge_state == 1 and self.modules > 0:
                self.modules -= 1
                car.receive_module()
                break

            utpov += car.update_state()

            if car.is_fully_charged():
                self.modules += car.modules
                self.car_data.append(car.get_data())
                self.remove_car(car)

        self.out_power.append(utpov)
        self.module_uptime.append(NUMBER_MODULES - self.modules)
        return

    def plot_data(self):
        time_array = range(self.t)
        for car in self.cars:
            self.car_data.append(car.get_data())

        for data in self.car_data:
            soc, name, t0, title = data.values()
            plt.figure(name)
            l = len(soc)
            time_to_charge_hrs = l/3600
            title = title + ", time to charge: {:.2f} [hrs]".format(time_to_charge_hrs)
            t = range(t0, t0+l)
            plt.plot(t,soc)
            plt.grid(True)
            plt.xlabel('Time [s]')
            plt.ylabel('SOC')
            plt.title(title)


        out_power_normalized = [p/MODULE_POWER for p in self.out_power]
        end_time = out_power_normalized.index(0,8000)
        plot_end = end_time + 1000
        plt.figure('Modules used')
        plt.plot(time_array[:plot_end], self.module_uptime[:plot_end])
        plt.plot(time_array[:plot_end], out_power_normalized[:plot_end])
        plt.legend(['Modules ', 'Out power'], loc = 1)
        plt.text(end_time//1.5, 0.2, r'$T_{tot} = $' + '$ {}$'.format(end_time) + "$s$", fontsize=15)
        plt.grid(True)
        plt.xlabel('Time [s]')
        plt.ylabel('modules and out power/module power')
        plt.show()
        return

def simulate(seconds: int = 60*60*4, number_modules: int = 5, car_arrival_times: list = [0, 500, 1000, 2000, 2250]):
    #Skulle vilja ha ett text-dokument med stats utspridda över någon bilfördelning förankrat i verkligheten. Så 10% av stats är de för model 3 osv.
    car_stats = [(110, 0.13, 150, 'Senor Strömslukare'), (75, 0.195, 100, 'Bettan'), (55, 0.291, 67, 'Gunnar'), (95, 0.195, 100, 'Ada'), (36, 0.39, 50, 'Leif')]
    indx = 0
    s = Supervisor(number_modules)
    for t in range(0, seconds, TIMESTEP):
        if t in car_arrival_times:
            s.new_car(Car(t, *car_stats[indx]))
            indx += 1
        s.supervise()
    s.plot_data()
```

```
        return

if __name__ == '__main__':
        simulate(number_modules = NUMBER_MODULES)


# Bil1   Anländer direkt    Batt storlek 110 kWh - strömslukaren
# Bil2   Anländer 1000s    Batt storlek 75 kWh          - bettan
# Bil3   Anländer 2000s   Batt storlek 55kWh            -gunnar
# Bil4   Anländer 4000s    Batt storlek 95 kWh          - ada
# Bil5   Anländer 4500s    Batt storlek 36 kWh          -Leif
```